USE OF A GYRATORY TESTING MACHINE TO APPLY SIMULATED TRAFFIC TO BITUMINOUS CONCRETE

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by

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Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Final Report

USE OF A GYRATORY TESTING MACHINE TO APPLY

SIMULATED TRAFFIC TO BITUMINOUS CONCRETE

TO: K. B. Woods, Director
Joint Highway Research Project

January 7, 1964

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 2-4-20
Project: C-36-6T

Attached is a Final Report entitled "Use of a Gyratory Testing Machine to Apply Simulated Traffic to Bituminous Concrete". The report has been authored by Mr. Robert E. Hughes under the guidance of Professor W. H. Goetz. Mr. Hughes also utilized the research reported as the basis of the thesis requirements of an MSCE degree which he recieved in January 1964.

This report is the Final Report on a research project entitled "Evaluation of Indiana Bituminous Concrete Using the Gyratory Testing Machine" which was approved by the Board on March 20, 1963.

The report is submitted for the record.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Secretary

HLM:bc

Attachment

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Final Report

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by

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Project: C-36-6T
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Lafayette, Indiana

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ABSTRACT

Hughes, Robert E., MSCE, Purdue University, January 1964. Use of a Gyratory Testing Machine to Apply Simulated Traffic to Bituminous Concrete. Major Professor: William H. Goetz.

A laboratory study was conducted to determine how to use the gyratory testing machine as a device to apply a loading action to bituminous concrete specimens that will produce effects similar to the rutting and shoving types of failure created in pavements by traffic action.

The gyratory machine variables of ram pressure, upper roller air pressure and gyration angle were varied to determine their individual effect upon the laboratory specimen. The variable gyratory machine testing was performed on bituminous mixtures of two different aggregate gradations, both at a constant asphalt content. Hveem stability and bulk density measurements were made on the test specimens after they had been subjected to a variable number of revolutions.

Following study of the gyratory machine variables, one combination of these was selected to represent simulated traffic action for use in performing tests upon mixtures of several aggregate gradations at a varying asphalt content. Also involved in the research was an investigation of the effect of gyratory machine testing on the aggregate gradation of mixtures. A gradation analysis was performed upon the aggregate portion of specimens following testing in the gyratory machine for a variable number of revolutions.

Use of the gyratory testing machine as a traffic simulating device produced changes in Hveem stability and bulk density of laboratory specimens that are thought to be characteristic of property changes that may occur in actual pavements. Results of the study showed what range in magnitude of individual gyratory machine variables might best be utilized for a traffic testing procedure. The gyrograph recording of the angle of gyration the specimen is undergoing during the test has poor sensitivity to change in stability of the specimen. Gyratory machine performance of bituminous mixtures of variable asphalt content are interpretated in terms of Hveem stability, bulk density and air void content.

The simulated traffic testing of the mixtures of different aggregate gradations at the same asphalt content showed that a difference in performance could be expected from them. It also showed that the Hveem stability design criteria did not give a reliable indication of how a mixture will perform in the gyratory machine under conditions of operation proposed to represent those of service. No significant aggregate degradation resulted from use of the gyratory testing machine as a traffic simulating device in the laboratory.

The overall conclusion is that the gyratory testing machine shows promise that it can be used successfully as a traffic simulator device for the purpose of producing effects similar to rutting and shoving types of failure created in pavements by traffic action, when used in a manner such as described in this study.

INTRODUCTION

Bituminous concrete pavements must be designed so that loss of stability in service will not result. To accomplish this requires application of known design principles and some means of predicting performance in service. The attainment of desirable bituminous pavements cannot be achieved unless proper laboratory evaluation tests are made on the raw materials and proper scientific laboratory control exercised in the production and laying of the mixtures (1). Constant research is necessary to eliminate the deficiencies of procedures devised in the past.

First in importance in the laboratory testing of bituminous concrete mixes is the formation of a laboratory specimen that represents the mixture as it is used in service (8). To do this the laboratory test specimens must be compacted to strengths, densities and aggregate orientations that as nearly as possible approximate those developed in the actual pavement under construction compaction and traffic action. The compaction technique which does not give the same results as pavement consolidation with any type of mix poses a threat to the discovery of the actual condition that will appear in time (26).

The Indiana State Highway Commission currently uses the Hveem design procedure with a mechanical kneading compactor for fabricating laboratory specimens with mixture properties comparable to the actual pavement in service. Gaudette (7) states, "The kneading compactor is recognized as one of the most reliable methods of compaction now in common use; however, the point to be emphasized is that although it simulates field compaction to a higher degree than earlier types of compaction used in the laboratory, there is a need to improve the compaction technique to reproduce the field condition better." It should also be recognized that the equipment and procedures used in the laboratory to fabricate test specimens are not readily changed, due to the economics factor as much as anything, and any research or mixture evaluation testing that is conducted should be carried out through the use of the existing equipment.

Another important phase of laboratory testing is that of subjecting the fabricated specimens to a loading that will simulate the loadings on actual pavements due to traffic coverage. Through such testing an evaluation can be made of the load-carrying characteristics of pavement mixtures that vary in aggregate type, grade of bitumen and aggregate gradation. The ability of an asphalt pavement to carry traffic loads is primarily dependent upon the mineral aggregate (25). This ability depends on internal friction and on the mechanical arrangement of interlocking of the individual particles of the mass, which are greatly affected by the degree of compaction, particle shape or angularity and surface texture in addition to the aggregate grading. The forces that cause compaction also cause breakage and wear at the points of contact of the aggregate materials. Such degradation may reduce the angularity of aggregate particles, and thus decrease the interlocking, which in turn results in a loss in stability of the mixture with resulting shoving, distorting, and corrugating (23).

The gyratory testing machine has been used recently in studies dealing with the design and testing of bituminous mixtures in the laboratory. Moavenzadeh in his study of aggregate degradation in bituminous mixtures stated that of all available methods, gyratory compaction appeared to be the most promising one to produce specimens similar to the field mat from the density and structure standpoint (23). In a report on the development of the gyratory testing machine issued by the U.S. Army Corps of Engineers it was said (5), "The use of the gyratory machine to simulate traffic testing appears logical since any desired vertical load can be applied simultaneously with a slight self-adjusting kneading action to simulate the load and movement of the pavement under traffic." The Ohio Department of Highways has developed a gyratory compactor for application to construction control and bituminous mix design (15).

It would seem very worthwhile to apply the gyratory testing machine as a traffic simulator to bituminous mixtures currently used by the Indiana State Highway Commission and designed by Hveem procedure using the mechanical kneading compactor. This could then provide the basis for an evaluation of the design criteria with regard to what it represents in terms of future pavement stability performance.

REVIEW OF LITERATURE

The increased stresses produced in bituminous highway pavements by modern traffic have caused frequent failures in stability as evidenced by rutting and shoving. Such failures have lead to a major problem in design of adequate bituminous paving mixtures. Present traffic volumes and heavy wheel loads are forcing highway engineers to develop sound design and construction procedures for each layer in order to prevent early deterioration of the entire pavement (11). There seems to be a shortage of knowledge concerning the actual condition brought out in pavement by traffic action. Wood and Goetz (34) state:

> "In recent years, rutting has become a problem in certain types of bituminous concrete overlays. The highways affected are generally those subjected to numerous repetitions of heavy wheel loads. Cores taken from the wheel tracks and from between the wheel tracks indicate very little difference in the density of the mixture in these two areas. Over a period of time, density values of cores indicate that densification of the entire overlay has taken place. This might indicate that rutting is a type of plastic or permanent deformation."

Hveem and Vallerga (13), in a density-stability study, wrote:

> "--- asphaltic pavements often appear to be satisfactory and stable for a period of time, perhaps for several years, and then finally develop evidence of instability in the form of grooving, surface waves and other distortion. There are, of course, several contributing factors which may be responsible for this delayed change in appearance. It requires time for instability to become evident where a very viscous or low penetration asphalt is involved. It is also true that in certain cases the mineral aggregates may break down or degrade, producing more fines and in effect changing the mix composition. But a third cause is the increase in density caused by traffic compaction."

Many failures such as these are a result of increased traffic loadings. Modern traffic compaction may cause a stability failure in a much shorter period of time than a similar pavement of the past by having increased the time rate of densification and air voids reduction in the bituminous pavement. High temperatures in combination with heavy loadings increase the effect on pavements by such loadings. When a fresh mix is exposed to warm temperatures accompanied by heavy traffic, the material densifies rapidly in the upper layers and the void content may be reduced to the point where asphalt is actually flushed to the surface (21). During the warmer seasons of the year when sufficient energy is absorbed from the sun to soften or render the bituminous binder fluid, asphaltic paving mixtures, notably those containing excessively high bitumen percentages, are liable to displacement under traffic (25). It is not to be forgotten that asphaltic concrete is essentially a plastic material and as such it undergoes minute deformations and slow consolidation under traffic, regardless of its initial state of densification (21).

Present day bituminous paving mixtures must be designed with a lower asphalt content than those of the past to compensate for the increased densification caused by traffic. Generally the use of less asphalt decreases resistance to cracking but increases resistance to plastic deformation (20). With a high asphalt content, a state of flushing may be reached early in the life of the pavement. Most paving engineers today have learned that it is very unwise to use enough asphalt to fill all the voids in the mixture and many specifications include some limiting clause which regulates the amount of asphalt depending upon the void space available (13).

Since traffic compaction causes densification of the pavement, construction compaction should not only produce a mixture of adequate stability and durability, but allow for further compaction by traffic. Metcalf (20) states:

> "The observation that densification is usually greater in lean than in rich mixes can be attributed to the fact that the former are compacted initially to a lesser degree relative to ultimate minimum void content. Aggregate voids can also be reduced to a smaller ultimate space in lean mixes and thus a greater change is possible before ultimate density is reached."

Nevitt (26) summarizes:

> "We must prevent overconsolidation and resulting loss of strength or poor design in mixes, too little asphalt, or other results which in the end propose equally unsatisfactory pavements. It is not believed that such methods will be too difficult to develop provided the approach is made from a fundamental standpoint."

A proper laboratory approach to bituminous pavement design should be very critical of the method of sample fabrication. The laboratory sample should approximate as nearly as possible the bituminous concrete pavement as it will exist in the field and this requires the method of molding to duplicate construction compaction and traffic compaction. The compaction technique which does not give the same results as pavement consolidation with any type of mix poses a threat to the discovery of the actual condition that will appear in time (26). In a paper concerning the compaction of bituminous mixes, Nevitt (27) proposed that:

> "The compaction equipment used should satisfy the following requirements:
>
> 1. The compacted laboratory samples must duplicate the corresponding pavement in its proportion of ingredients, their internal arrangement, and their condition. This latter implies uniformity (lack of segregation) and condition (lack of degradation).

2. The compaction equipment should be, if possible, simple and inexpensive.

3. It should facilitate speed in testing. This implies both rapidity of compaction and the ability to compact a number of samples in identical fashion at the same time.

4. It should suit, or permit with minimum adjustments, the use of different mold sizes or shapes without change in the condition of requirement 1.

He went on to say that these objectives do not seem generally met in present day methods.

Endersby and Vallerga (6) write:

"---the general problem of correlating laboratory tests with field work should be considered. There has been some tendency in the past to make one or both of two assumptions: One, that laboratory compaction should produce as dense a specimen as possible; the other, that it should produce as stable a specimen as possible. The wisdom of these assumptions is very doubtful. The real objective is to produce a specimen that is as nearly as possible like the pavement developed under road traffic; this road pavement is not necessarily either as dense or as stable as the most dense and stable laboratory specimen."

They go on to say:

"In running down possible defferences between laboratory and field compaction the first fairly obvious point is that the pavement as laid down has no rigid mold around it, which is a major factor in both compaction and particle arrangements in laboratory specimens. The chief difference between any kind of mold compaction and roller or pneumatic-tired compaction in the field, is that adjacent to the roller or tire the particle can move laterally or longitudinally with considerable freedom; and with a fair amount of freedom vertically also."

Several requirements for laboratory compaction of asphaltic concrete specimens were followed by the Texas Highway Department in their development of the gyratory shear method of compaction, as discussed by Ortolani and Sandburg (28):

"Several criteria were set up as required of any molding method evolved; first, the method must be equally adaptable to the field control of the mix as to the design. An excellent but lengthy design procedure would be useless in the field as a control test. Second, the method should yield essentially the same density, or void ratio, as that obtained with any molding procedure should approximate that of the pavement after some time in the road. A third requirement of the molding method was to approximate as nearly as possible, the aggregate degradation obtained under field conditions."

There are a number of procedures and a variety of equipment used today to mold bituminous concrete specimens. Some have been shown to give a specimen which duplicates closely the corresponding pavement in its properties, some have been severely questioned as to their ability to duplicate field compaction in the laboratory, but all the methods can probably be found to have inconsistencies when laboratory samples are compared to the asphalt pavement. Nevitt (26) remarks upon this:

"Regardless of the confidence apparently held in their techniques by the proponents of the various procedures, data are needed on the progress of traffic consolidation and the correspondence therewith of samples compacted by the various means proposed. The scrutiny given these correlations will have to be suitable as well as exact. Many methods will give a rough correspondence from which design can be made with a reasonable degree of accuracy for the usual mix. If progress is to be made, we must go beyond this. We must know that the methods used really duplicate either the compaction technique, if that is the subject under consideration, or and more importantly - road consolidation."

The mechanical kneading compactor has many advocates in the field of bituminous concrete design. The condition produced by the roller and traffic can be approached closely if pressure is applied through a loaded area smaller in diameter than the mold such that the material gets pushed around the mold. This is the method used in the kneading compactor (6). Nevitt (27) says:

"The most serious criticism with certain approaches is their lack of duplication of the internal mat structure, such as the use of direct compression. Furthermore, most methods bring in effects not present in the road, such as arch action in the mold. The equipment which seems to have the most general approval is the California machine."

In 1937 the first kneading compactor was constructed and placed in operation in the laboratory of the California Division of Highways (13). Endersby and Vallerga said in a report on laboratory compaction methods (6), "---It is considered that the Triaxial Institute kneading compactor produces a specimen with the density and particle arrangement manifested by the asphalt pavement when subjected to the compactive effort of traffic for a given period of time, as evidenced by the field correlations and accumulated experiences of the California Division of Highways and the California Corporation with compactors employing the same kneading principle."

Writing on work performed by the Washington State Highway Commission, Minor (21) says:

> "Densities obtained with the kneading compactor compare favorably with densities in the roadway after one or more years of service. Further data show that the density of a bituminous pavement generally decreases with depth and that the kneading compactor prepares a specimen with similar density distribution.
>
> "We feel that the kneading compactor is the best tool presently available for laboratory preparation of bituminous mix specimens. One rather common criticism of the compactor that has not, to our knowledge, been discussed to any degree in previous reports is that it does not produce a specimen with uniform density from top to bottom. That observation is true but it is, in our opinion, a point in favor of the compactor rather than a justifiable criticism of it."

After a year or more of service pavements develop a density gradient due to traffic consolidation. Endersby and Vallerga (6) report that:

> "1. Asphaltic-mix test specimens prepared by kneading compaction generally have higher bulk specific gravities than specimens of corresponding composition prepared by the other compaction methods used in this study. This difference is rather large at low asphalt contents and small at high asphalt contents, and the peaks for kneading compaction invariably occur at a lower asphalt content.

2. The curves established by the five mechanical stability tests, for the various compaction methods used, indicate that in all cases specimens prepared by kneading compaction give higher "stability" values in the lower ranges of asphalt contents and lower "stability" values in the higher ranges of asphalt contents, resulting in greater sensitivity to asphalt content for all test methods.

8. In general, the effects of different compaction methods are frequently greater than those of aggregate type, asphalt content, or test method."

The kneading compactor has been found to be superior to other compaction methods in the laboratory duplication of the field pavement as evidenced by a number of studies, a few of which are reported here. According to Vallerga (33):

"There is little doubt where maximum stability occurs for the kneading methods of compaction; whereas for static load the point of maximum stability would be difficult to define, particularly when a mix is to be designed with as much asphalt as possible in order to impart durability and water tightness without sacrificing stability. Similar results have been obtained by other investigators, who have pointed out this failing of the static method of compaction."

Another study, conducted by Vallerga and Monismith several years after the above one by Vallerga, produced similar results in a comparison of kneading compaction and static compaction (24).

In a paper that was included in the Compaction Symposium presented by the Association of Asphalt Paving Technologists in 1957, McRae (18) has the following to say about impact compaction:

"Investigations have shown that increasing the number of impact blows in the laboratory to obtain the high densities required is infeasible, if indeed, it is even possible to attain the density at all by this method without excessive degradation of the aggregate.

"It has also been long recognized that the stabilities obtained on laboratory specimens compacted by impact are higher than the stabilities on actual pavement cores of equivalent density and bitumen content which seems to indicate a difference in structure or aggregate particle arrangement and distribution."

Nevitt (26) says, "---impact effects are accomplished by high stress intensities, correspondingly high inertia and flow resistances, and some degradation." He also remarked that "---vibration superficially appears a quite different compacting agency than traffic." Gaudette (7) states, "The kneading compactor is recognized as one of the most reliable methods of compaction now in common use; however, the point to be emphasized is that although it simulates field compaction to a higher degree than earlier types of compaction used in the laboratory, there is a need to improve the compaction technique to reproduce the field condition better." Smith (31) has said, "Kneading-type compaction is known to yield specimens approximating closely the particle orientation and stability properties obtained in actual field construction."

Gaudette performed a laboratory investigation on the applicability of the kneading compactor to bituminous concrete design in the State of Indiana and concluded (7):

> "The results of this investigation give evidence that the kneading compactor does not produce a compacted bituminous specimen having the same physical characteristics as the material after construction and traffic compaction in the field under Indiana conditions. Cut sections of field and laboratory compacted specimens from this study have shown that the kneading compactor does not produce particle orientation of the same type as produced by construction equipment and traffic in the pavement. In the pavement the particles arrange themselves in a position with the long axis horizontal, but the kneading compactor produces a random particle arrangement. Furthermore, observation shows that the density variation throughout a specimen using standard compaction with the kneading compactor does not follow the same pattern as the variation in a field compacted specimen."

Another criticism of the kneading compactor is made by Hannan (10), who writes, "Using the current compaction procedure, this machine will produce excessive aggregate fracture in very open-graded mixtures, and for this reason does not simulate the true field compaction of such a mix."

The preceding discussion brings out the great importance that is placed upon the fabrication of laboratory specimens to simulate the pavement in the field. Another important objective of the laboratory design and study of bituminous concrete mixes is a determination of the stability property of compacted specimens. Monismith and Vallerga (24) believe that, "---stability is best defined as a load to cause a certain amount of deformation, said deformation depending upon expected field conditions, and that only a form of triaxial compression test will properly measure this property." Some type of stability test is desirable to determine the ability of a bituminous concrete mixture to resist rutting and shoving when in a compacted state.

Among the present test methods for obtaining a stability evaluation of bituminous mixtures are compression tests, bearing tests, the Marshall method and the Hveem Stabilometer (22, 32). Stevens (32) has the following to say of various types of tests, considering first the unconfined compression test:

> "The simplest of the compression tests is the unconfined compression test which is still used. The major drawback to this method lies in the fact that materials in an actual road structure are not in an unconfined state. In the road, surrounding material applies a constraining force to the section being subjected to load, and so one would expect that this constraining effect might affect different materials in different manners.
>
> "In principle, bearing tests have considerable merit because in general the specimen is constrained in a mold which supplies lateral restraint.
>
> "However, this type of [bearing] test is also subject to certain inherent disadvantages which are of unknown magnitude. Although lateral restraint is supplied to the specimen by the mold, it is essentially unyielding, whereas lateral restraint which occurs in a pavement is of a yielding type.
>
> "In a test involving the volume of construction that is now based on Marshall Test criteria, there are serious considerations. To date no attempts have been made to develop proper test limits for soft asphalt or cutback asphalt mixes. Nor has there been any serious effort to evaluate the test on a wide range of aggregate or on sharply divergent aggregate gradations. In

spite of these very necessary studies which should be made, there has been a rapidly spreading tendency, apparently never intended by the Corps of Engineers, to apply the method as a general analysis and design tool.

"In judging the ability of a paving mix to be stable within itself, the principal issues are how much of the load will it transmit vertically to the course below it, and how much of the load will it transmit laterally, thus tending to shoving, rutting, and upheaving. Triaxial type compression tests, and Hveem Stabilometer in particular, measure this lateral shoving tendency of a mix. If it is too great, the mix will be unstable in itself.

"The Smith Triaxial test is similar to the Hveem Stabilometer in principle. Lateral thrust of the specimen under load is measured but here the complicating factors of the base and loading plates are eliminated by using a tall specimen. ----It is not surprising that results from the Smith and Hveem apparatuses are virtually parallel.

"The principle objections made to the Smith method are the cumbersome size of the test briquettes, 8 in. x 4 in., and the length of time required to test a briquette which may range from about an hour to as much as several hours."

Review of Stevens' discussion of stability testing methods brings one to the conclusion that the Hveem Stabilometer might be better suited for this purpose than the other methods. From the standpoint of speed and economy, the Hveem Stabilometer appears to be more favorable than the other testing methods. Hveem and Davis (12) have the following to say in regard to this:

"At the present time the trend of thinking and work conducted by the Triaxial Institute indicates that for day-by-day routine testing in highway laboratories where the volume of work is very large and the need for rapid testing becomes acute, the Stabilometer method seems to promise the greatest overall speed of operation, which means that a large number of individual tests can be performed. This is an important item when dealing with materials from sources that are inherently nonuniform and variable."

The Hveem Stabilometer has an additional advantage over other stability testing methods in that it has been correlated with field performance of pavements to a high degree. Stevens (32) says:

"One of the main reasons for the growing popularity of the Hveem Stabilometer rests in the wide correlation with field performance from which the test criteria were derived. A great variety of mix types were analyzed throughout the State of California before test conditions and limits were established. To date few failures have been encountered in pavements designed with the aid of this apparatus."

From a study of density vs. stability, Hveem and Vallerga (13) concluded:

"From the evidence of these and other test data as well as evidence furnished by pavement performance, there is no general relationship between density and stabilometer values.

"There is a very high degree of correlation between stabilometer results and pavement performance and little correlation between stabilometer and the density of the mixture except that the stabilometer results are invariably low when the void spaces are filled or nearly filled with asphalt."

In regard to bituminous concrete design, Endersby and Vallerga believe that it is questionable whether any of the test methods except the Stabilometer would provide a sound basis for the selection of a design asphalt content (6). The Stabilometer also has the valuable asset that it can be applied to the testing of pavement cores. There are a number of references that describe the operation of the Hveem Stabilometer (7, 10, 22).

It is desirable to know how a bituminous paving mixture will perform under traffic. There is always the danger that a particular mixture, apparently satisfactorily designed by a laboratory design method, may be so affected by the action of traffic as to fail in stability. To prevent such a happening it may be desirous to test the compacted laboratory specimen under a loading system that simulates the traffic action on pavements. In this manner it might be determined how the characteristics of the bituminous concrete will change under traffic and if there exists a possibility that failure may develop early in the life of the pavement due to such changes.

Nevitt (26) points out the importance of a laboratory design that will include effects of traffic by saying:

> "The road structure must be designed for its most probable condition of failure. The pavement is an important part of this road structure and its structural quality should be evaluated under corresponding conditions. A laboratory sample of the mix should consequently be tested after compaction to the degree corresponding to this road life, and by a method which reproduces the pavement structure as well as density."

It is evidently as important here as it is for the laboratory compaction of samples to reproduce as nearly as possible those conditions that exist in the field for the respective process being considered. Vallerga (33) says, "The specimen prepared in the laboratory must in all respects be representative of a field-compacted specimen if laboratory results are to be truly indicative of field performance." Nevitt (27) said elsewhere:

> "Proper design requires testing a sample simulating the pavement after use. This demands laboratory compaction which duplicates traffic action.
>
> "For unqualified acceptance the laboratory compaction must be shown to duplicate that from traffic."

A relatively new machine in the field of bituminous concrete pavement design is the gyratory testing machine, which is based on a manually operated compactor originally developed by the Texas State Highway Department (4). This machine was developed in an attempt to fill the needs for an improved compaction apparatus. The gyratory testing machine is believed (4) capable of:

> "(a) Producing the high densities that develop under channelized traffic of heavy wheel loads; (b) producing specimens with stress-strain characteristics similar to those of actual pavement samples of equal density and bitumen content; (c) predicting the number of load applications a paving mixture can withstand before failure; (d) predicting the design bitumen content independently of voids criteria; and (e) providing a more positive and faster plant-control test.

> "Extensive laboratory and field tests proved the principle of the gyratory testing machine to be sound and its predictions to be more accurate than those of other previously established test methods."

The bituminous concrete design of the Texas State Highway Department is based on the principle that the gyratory method of compaction has the ability to produce a laboratory specimen whose density and degradation characteristics approach closely those of a satisfactory bituminous concrete pavement (28, 29). The operation of the gyratory testing machine is described in several references (5, 19, 28, 29).

The gyratory testing machine appears applicable as a loading device to simulate traffic action. McRae and Foster (19) comment:

> "The operation of the gyratory machine using the oil-filled upper roller has been found to be most satisfactory for design and control tests, and the operation with the air-filled upper roller shows more promise when using the machine for research studies on the effect of long-time repetitive loading with deformations of small magnitude such as usually occur in the phototype. Also operation with the air cell lends itself better to the study of such variables as type of asphalt, type of aggregate gradation, and other factors because the machine is more sensitive to stress variations when operated in this manner."

The gyratory testing machine certainly appears to be worthy of consideration from the standpoint of several design uses. In addition it seems to be very applicable to the research phase of bituminous concrete design and testing. Future research studies and field correlation studies may show how true this really is.

PURPOSE AND SCOPE

This research study was proposed as a laboratory investigation of the stability properties of Indiana bituminous concrete mixtures under simulated traffic loadings. The gyratory testing machine was to be utilized as a traffic simulating device to test specimens fabricated in the kneading compactor. The upper roller of the gyratory machine, when used in conjunction with an air-filled pressure chamber, gives a constant force method of operation that is thought to simulate the effect of traffic and for this reason was selected for use in this study.

The objectives of this investigation were three-fold initially. First, it was desired to establish a testing procedure for the use of the gyratory machine as a traffic simulating device. In order to accomplish this a study was conducted to determine how the gyratory machine variables influence the test specimen during operation. Variables studied were the vertical ram pressure, gyration angle and the upper roller air pressure. From this it could be determined what combination of variables would be most suitable to represent simulated traffic action. Once this was established, the amount of simulated traffic applied would vary directly with the number of revolutions in the gyratory machine.

Secondly, it was desired to evaluate the resistance of Indiana bituminous concrete mixtures to traffic loadings by subjecting laboratory prepared specimens to simulated traffic in the gyratory testing machine and to determine values of Hveem stability for kneading compactor specimens that would indicate a bituminous mix of satisfactory stability as tested in the gyratory machine. The object here was to evaluate the Hveem design criteria with regard to what it represents in terms of future pavement stability performance.

The final objective of the original purpose was to determine a procedure for fabricating laboratory specimens composed of both a surface-course mixture and a binder-course mixture such that they would better represent the bituminous concrete pavement in the field than do laboratory specimens composed solely of one type of mixture. It was anticipated that a comparison between the stability properties of the composite specimens and the stability properties of individual course specimens would be of some value in evaluating present design and testing procedures. However, after the research was partially completed it was decided that even if a composite specimen fabrication procedure was devised, which would be quite lengthy to obtain, the end result would not justify the means. That is, little of practical value could be derived from testing of composite specimens as compared to the testing of individual course specimens.

Also encompassed in the study was a gradation analysis of aggregate which had been separated from the asphalt of specimens tested in the gyratory machine for variable numbers of revolutions. This was performed to provide a check on possible aggregate degradation during testing in the gyratory machine.

The scope of the research included the study of three surface gradations and one binder gradation. Testing for variable asphalt content was performed with one surface gradation and the binder gradation, each for three asphalt contents. For the portion of the research dealing with study of gyratory testing machine variables, two duplicate specimens were usually prepared for each number of revolutions at which test results were desired. When testing at variable asphalt content, three duplicate specimens were prepared for each point. The total number of specimens fabricated for the research study was approximately 300.

MATERIALS

Materials used in this study were similar to those commonly used by the Indiana State Highway Commission in their bituminous mixtures. Aggregate materials were obtained from nearby sources. A description of the materials used in the research follows.

Mineral Aggregates

The types of aggregates used and their source are as follows:

1.	Limestone	Greencastle, Indiana
2.	Dune sand	Monon, Indiana
3.	Natural sand	West Lafayette, Indiana
4.	Limestone filler	Greencastle, Indiana

The limestone, natural sand and limestone filler were obtained from commercial sources, while the dune sand was not. The commerically produced aggregates were obtained in a washed condition.

Each type of mineral aggregate was sieved in the laboratory into the sizes desired. The limestone aggregate was washed following the sieving operation.

The aggregate materials were tested for specific gravity and absorption according to ASTM Methods C 127 and C 128, and the results are shown in Table 1.

Aggregate gradations used in this research were selected to meet the Indiana State Highway Commission specifications for surface-course and

TABLE 1

RESULTS OF TESTS ON AGGREGATES

Size	Material	Bulk Specific Gravity*	Apparent Specific Gravity*	% Absorption
3/4"-1/2"	Limestone	2.64	2.68	0.88
1/2"-3/8"	Limestone	2.63	2.68	1.10
3/8"-#4	Limestone	2.67	2.71	0.90
#4 -#6	Limestone	2.63	2.71	1.74
#6 -#8	Limestone	2.62	2.70	1.94
#8 -#16	Natural Sand	2.59	2.72	2.77
#16 -#50	Natural Sand	2.60	2.70	2.45
#50 -#100	Natural Sand	2.63	2.70	2.63
#100-#200	Dune Sand	2.59	2.65	1.27
Pasing #200	Limestone	2.71	--	--

* - average of three determinations

binder-course type hot asphaltic concrete mixtures, with the exception of one. The one exception was selected from another research study (7) because the study contained field results using this gradation. It was considered that this might be useful in this project for laboratory-field correlation purposes. This gradation is referred to as gradation B in this study, as it was in the reference from which it was obtained. A total of three surface gradations and one binder gradation were used. They are listed by component sieve sizes in Table 2, and compared to Indiana specification limits in Figures 1 and 2. The surface course gradation H was chosen to have a higher sand content than surface course gradation A.

Asphalt

A 60-70 penetration grade asphalt was used in this study. This is the penetration grade currently used by the State of Indiana for hot asphaltic concrete. Results of tests on this asphalt are presented in Table 3.

TABLE 2

AGGREGATE GRADATIONS

Percent Passing

Sieve No.	Surface Gradation A	Surface Gradation B	Surface Gradation H	Binder Gradation D
3/4"				100.0
1/2"	100.0	100.0	100.0	80.0
3/8"	90.0	90.8	92.0	
#4	60.0	50.9	60.0	40.0
#6	45.0	41.3	54.0	35.0
#8	38.0	37.5	48.0	30.0
#16	25.0	32.1	36.0	20.0
#50	7.0	8.0	16.0	8.0
#100	5.0	3.2	5.0	4.0
#200	3.0	2.6	3.0	1.5
Total Retained on #6	55.0	55.2	46.0	65.0

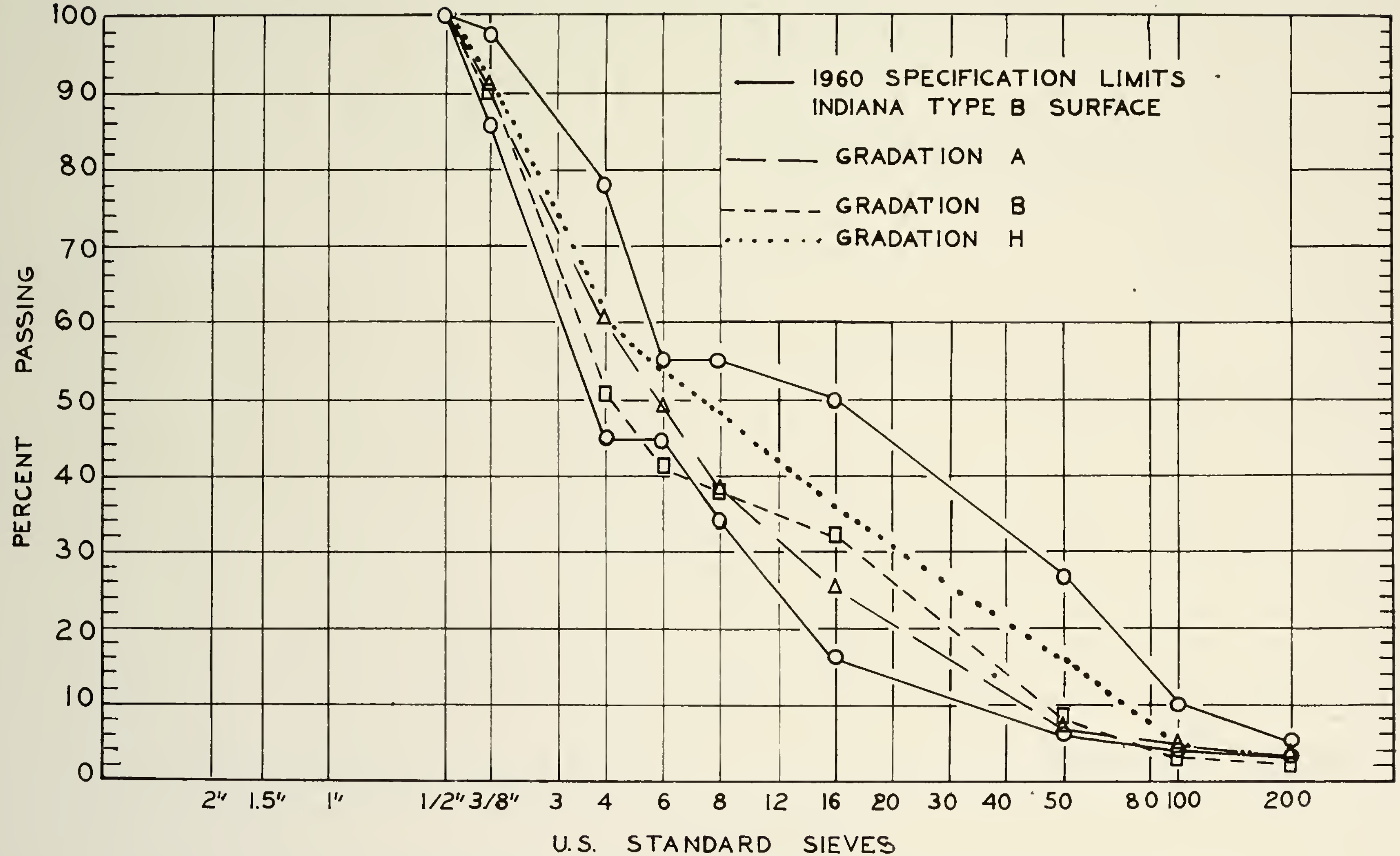

FIG. 1 AGGREGATE GRADATION CURVES—TYPE B SURFACE

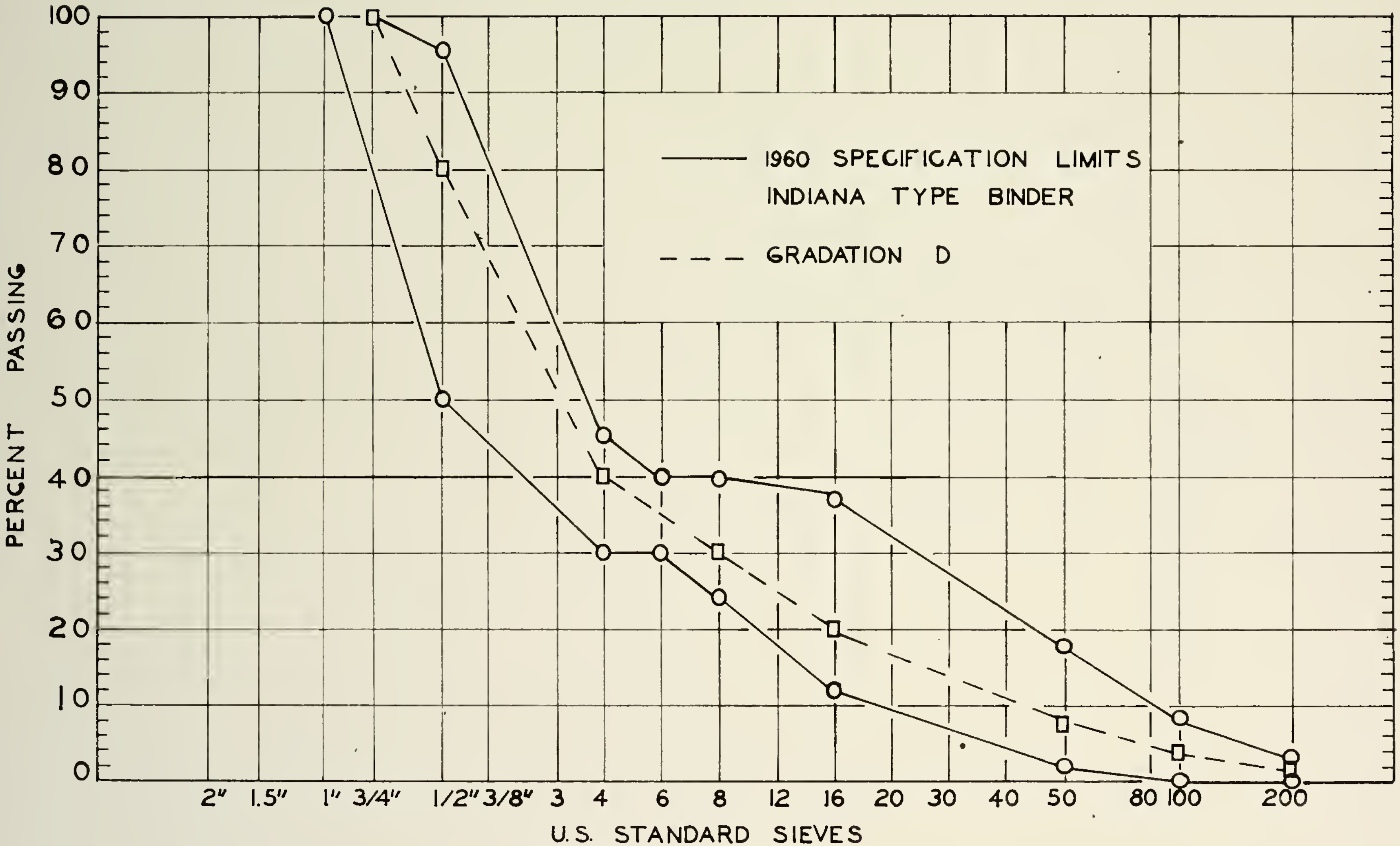

FIG. 2 AGGREGATE GRADATION CURVES — BINDER

TABLE 3

RESULTS OF TESTS ON ASPHALT CEMENT

Specific Gravity @ 77°F	1.036
Softening Point, Ring and Ball, °F	124
Ductility at 77°F, 5 cm/min., cm.	100+
Penetration, 100 grams, 5 sec., 77°F	66
Penetration, 200 grams, 60 sec., 32°F	17
Loss on Heating, 50 grams, 5 hr., 325°F, percent	0.01
Penetration of Residue, percent of original	89
Flash Point, Cleveland Open Cup, °F	595
Solubility in CCl_4, percent	99.84

PROCEDURES AND EQUIPMENT

In this section the following sequence of operations is described:

Batching and mixing

Specimen fabrication

Traffic simulation

Stability measurement

Specific gravity measurement

Gradation analysis

Batching and Mixing

Aggregates that had previously been separated into component sieve-size fractions were batched in accordance with the accumulative batch weight formulas. The normal total batch weight used throughout this research study was 1200 grams. A Toledo scale sensitive to one gram was used to batch the cold dried aggregate.

Prior to mixing, the individual batches of aggregate were placed in a Peerless gas oven to preheat to the desired mixing temperature of $325 \pm 5^{\circ}F$. The asphalt used in this study was also preheated separately to the mixing temperature of $325 \pm 5^{\circ}F$. The mixing bowl and paddle were also heated to this temperature. The heated mixing bowl containing the heated aggregate was placed upon the scale and the desired percentage of heated asphalt, by weight of dry aggregate, was added. Mixing was performed with the use of a Hobart (Model A-200) electric mixer using a two-minute mixing time.

Following the mixing operation the asphaltic mixture was transferred to an 11 x 7 x 1-1/2 inch pan and placed in a Hotpack (Model 1412) oven provided with forced draft air circulation. The mixture remained here for a fifteen-hour curing period at a temperature of 140 $\pm$ 5°F.

Specimen Fabrication

All specimens for this research study were fabricated with the California kneading compactor, using a procedure outlined by the Asphalt Institute mix design manual (22). This procedure is briefly described here.

The mixtures to be compacted are heated to the compaction temperature of 230°F., and to prevent the mix from adhering to it, the compactor foot is preheated. Also preheated are the compaction molds. The mold assembly is prepared by placing the compaction mold in position in the mold holder with a 4-inch diameter paper disc inserted to cover the base plate. In order to have the base plate act as a free-fitting plunger during the compaction operation, a steel shim 1/4 inch thick is temporarily placed under the edge of the mold. The mold tightening screw is used to hold the mold firmly during the initial compaction procedure.

When the mixture has reached the required temperature, half is transferred to the compaction mold and a bullet-nosed steel rod is used to rod the mass twenty times in the center and twenty times around the edge. The remainder of the mix is transferred to the mold and the rodding procedure is repeated. The mold assembly is then placed into position on the mechanical kneading compactor and twenty tamping blows at 250 psi pressure are applied to accomplish a semi-compacted condition of the mix so that it will not be unduly disturbed when the full load is applied. After semi-compaction, the shim is removed and the mold tightening screw is released to allow movement of the mold. The compaction is completed by applying 150 tamping blows at a 500 psi compactor foot pressure. Following compaction, the mold and specimen are placed in the 140°F. oven for one and one-half hours, after which a "leveling-off" load of 1000 psi is applied by the "double plunger" method at a speed of 0.05 inch per minute and released immediately. After this load is applied the specimen is forced out of the mold.

Traffic Simulation

Simulated traffic testing of the bituminous samples was performed with the gyratory testing machine, shown in Figure 3 , using the air-filled upper roller to act as a variable-strain mechanism. The descriptions of gyratory machine action which follow can be found in several references (2, 5, 9, 19).

By referring to Figure 4, it can be seen that the roller assemblies which travel around the flanged upper portion of the mold chuck act as point loads 180 degrees apart. The pitch or angle of the flange can be set by adjusting the vertical position of these rollers and, if both rollers are set in a fixed position so that they cannot yield vertically, the angle found by a line passing through these two points is fixed. However, the pitch of the flange is not fixed with respect to rotation about a line through these points, and the mold chuck can, by rotation about this line, develop gyratory angles in excess of that made by the line through the two points where the rollers contact the flange. In the method of operation employing variable strain, not only does variable gyratory motion occur because of the condition just described but also because of variation in the angle between the rollers.

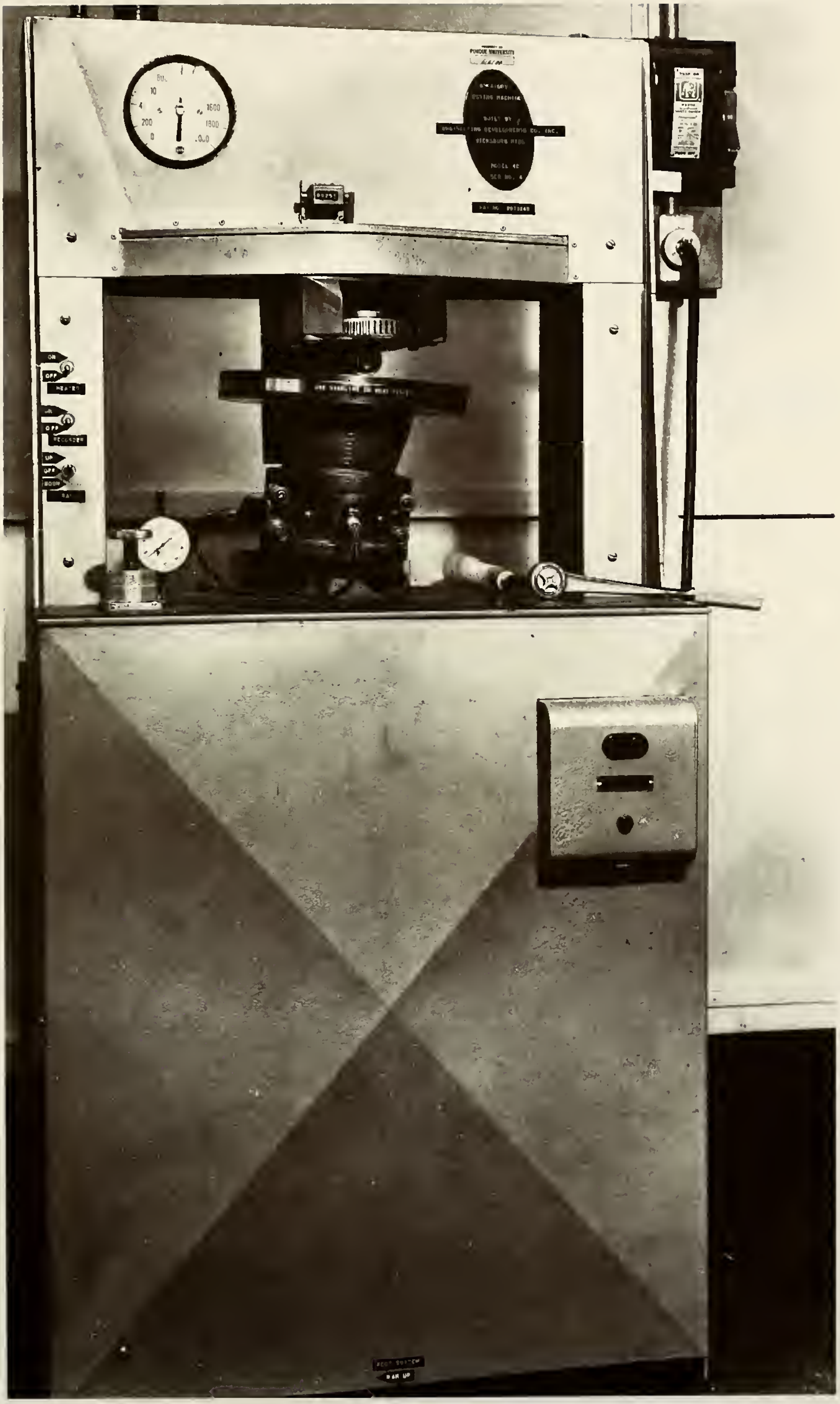

FIG. 3 GYRATORY TESTING MACHINE

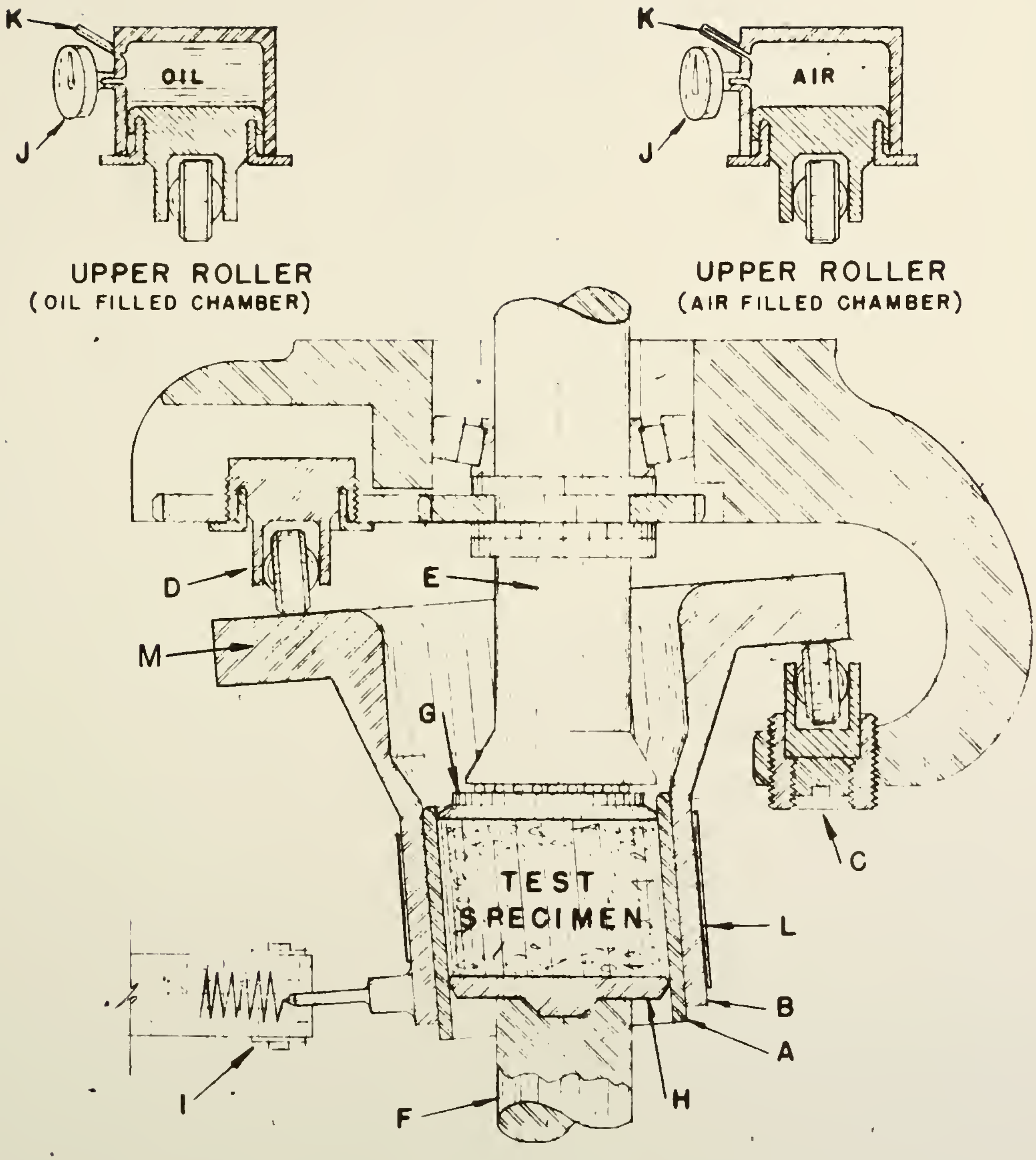

FIG. 4 SCHEMATIC SIDE VIEW OF SECTION THROUGH GYRATING MECHANISM
(AFTER CORPS OF ENGINEERS)

Key to Details of Figure 4

A. Specimen Mold

B. Mold Chuck

C. Lower Roller

D. Upper Roller

E. Upper Ram Shaft

F. Lower Ram Shaft

G. Upper Head

H. Lower Head

I. Gyrograph

J. Pressure Gage

K. Filling Valve

L. Heating Element

M. Chuck Flange

The setting of a gyration angle for testing is accomplished by placing the fixed roller in the gyratory machine and adjusting the bottom roller elevation until the angle of desired degree is recorded on the gyrograph as the roller assembly is turned 180 degrees by hand while a sample is in the machine. Although the machine is thus set for a certain gyration angle, the angle is not strictly a constant when the air-filled upper roller is used due to this roller's ability to change elevation.

The compactive effort that is applied by the gyratory machine to bituminous samples as a form of simulated traffic action can be varied by changing the vertical ram pressure, the upper roller air pressure, the gyration angle and the number of gyratory revolutions. The procedure for simulated traffic testing was based on the selection of a set combination of these gyratory machine variables to represent this action and to apply this to laboratory specimens under variable gyratory revolutions. In the first portion of this study the gyratory variables were each varied for the purpose of determining their effect upon the bituminous samples. Ram pressures studied were within the limits of 80 psi to 150 psi, representing current tire pressures. A maximum pressure of 100 psi could be registered by the upper roller air-pressure gauge. Gyration angles used in this study were 1 and 2 degrees.

Following the fabrication of the bituminous specimens in the mechanical kneading compactor and their removal from the compaction molds, the specimens were reheated to a testing temperature of 140 $\pm$ 5°F. They were then placed in the gyratory machine for testing. The chuck holding the steel mold is provided with a heating element; it was used to heat the mold to 140°F. temperature and to prevent loss of heat from the specimen during testing. Each sample was subjected to a specific number of gyratory revolutions, between 0 and 1000, and then removed and again placed in the 140°F. oven to await testing for stability. During testing, periodic recordings of the specimen height were made. Changes in the gyration angle, as recorded on a gyrograph by a mechanical pen recorder, are thought to reflect throughout the test the plastic properties of the specimen in the mold and also the effect the upper roller air pressure has on the angle of gyration.

Stability Measurement

Stability measurements of all bituminous specimens in this research study were made with the Hveem stabilometer. The testing procedure followed is that described in the Asphalt Institute's manual, Mix Design Methods for Hot-Mix Asphalt Paving (22). The test calls for the specimen to be tested at a temperature of 140°F. Specimens in this study were placed in the 140°F. forced-draft oven for a minimum period of one and one-half hours prior to testing. The total aggregate weight of 1200 grams for each aggregate gradation used in this study gave specimen heights within the range of 2.4 to 2.6 inches following gyratory machine loadings. Thus there were few cases where corrections had to be made to the stabilometer value.

Specific Gravity Measurement

The bulk specific gravity values of most of the specimens were determined following completion of the Hveem stabilometer test. The method followed was to compute the ratio of specimen weight in air to its bulk volume. Bulk volumes were obtained by soaking the specimens in water for a period of 24 hours and then recording the specimen weight when submerged in water and the saturated-surface-dry specimen weight in air. The dry specimen weight was recorded after cooling to room temperature, following completion of the Hveem stabilometer test, and prior to soaking. The formula used for the bulk specific gravity determination is as follows:

$$S.\ G._{bulk} = \frac{W_a}{V_b} = \frac{W_a}{W_{ssda} - W_w}$$

where:

V_b = bulk volume of specimen (cc)

W_a = weight of specimen in air (grams)

W_{ssda} = saturated-surface-dry weight of specimen in air (grams)

W_w = weight of saturated specimen in water (grams).

A small number of bulk specific gravities of specimens were determined by coating the specimens with paraffin for weight in water recordings. By this method the bulk volume of the specimen could be determined without soaking in water prior to making weighings. The following formula for bulk specific gravity using this method was used:

$$S.\ G._{bulk} = \frac{W_a}{V_b} = \frac{W_a}{W_{pa} - W_{pw} - \left(\frac{W_{pa} - W_a}{G_p}\right)}$$

where:

V_b = bulk volume pf specimen (cc)

W_a = weight of specimen uncoated in air (grams)

W_{pa} = weight of specimen plus paraffin coating in air (grams)

W_{pw} = weight of specimen plus paraffin coating in water (grams)

G_p = apparent specific gravity of paraffin.

Specific gravities using this method were determined following gyratory machine testing and prior to stabilometer testing.

Gradation Analysis

A certain number of specimens that had been subjected to simulated traffic action in the gyratory testing machine were selected for a study to determine the aggregate degradation that may have occurred from such action in the gyratory machine. The purpose was to study the possible aggregate degradation with number of revolutions in the gyratory machine. Asphalt extractions were performed in a Centrifuge Extractor, Soiltest model AP-175, with the use of benzene as the extracting agent.

The bituminous specimens selected for testing were cut in half with a masonry saw and the gradation analysis was performed on specimen tops and bottoms for comparison. Following extraction of asphalt from the mixture, a sieve analysis was performed on the remaining aggregate. The sieve sizes used were the same as those for the original gradation.

RESULTS

This section presents the results of this research study. It is composed jointly of graphical representations of data and a written discussion dealing with the evaluation of the results. All numerical data collected for the study have been placed in APPENDIX A and APPENDIX B. APPENDIX A contains data in terms of average values, which were used directly for preparation of graphical illustrations. APPENDIX B gives individual test results. The results are discussed under the following topics:

- The gyratory testing machine as a traffic simulating device
  - Similarities between laboratory and field
  - Influence of gyration angle
  - Influence of ram pressure
  - Influence of upper roller air pressure
- Traffic testing with the gyratory machine
  - Influence of variable asphalt content
  - Performance vs. aggregate gradation
- Effect of gyratory testing on aggregate gradation

The Gyratory Testing Machine as a Traffic Simulating Device

The variables of the gyratory testing machine as used in this study are the vertical ram pressure, the upper roller air pressure and the gyration angle. It was desired to determine how to use these to apply a simulated traffic loading to laboratory-compacted bituminous concrete specimens. In order to do this, tests were made with two different gradations using various combinations of the variables.

The vertical ram pressures used were 80, 100, and 150 psi, with emphasis upon the first two. These are representative of typical high tire pressures on highway pavements. Upper roller air pressures studied were a total of four and were within the range of 30 to 85 psi. This is the gyratory machine variable about which the least was known and for this reason was the primary variable to be studied. All but one of the combinations of gyratory variables included a pre-set gyration angle of one degree, the exception being two degrees. It was felt that a gyration angle of two degrees would be too severe for use in laboratory simulated traffic loading of bituminous concrete specimens for highway pavements. A U. S. Army Engineer, Waterways Experiment Station report (5) on the application of the gyratory testing machine to airfield pavements recommended that the gyration angle should not exceed two degrees, as greater angles caused lower unit weight and stability, which was said to be caused by "overshearing". Since this was based on studies of airfield pavements, the figure of two degrees may be too high for highway pavements.

Similarities Between Laboratory and Field

When looking at the curves of stability and density vs. number of revolutions for variable gyratory testing, it is important to consider how these properties will vary in a pavement subjected to actual traffic loadings. The stability would probably increase with traffic compaction until a maximum is reached and then decrease as a "flushed" condition either arises or is approached. Therefore a simulated traffic loading in the laboratory should produce the same characteristic curve. In the case of applying a simulated traffic loading with the gyratory testing machine, such a curve would be represented by a plot of Hveem stability vs. number of revolutions. It is known that traffic causes the majority of pavement densification within the first few years of pavement life. The gyratory machine should therefore produce the majority of densification in the laboratory specimen during the early number of revolutions.

A comparison of Hveem stability vs. number of revolutions at variable gyratory machine testing is shown in Figure 5 for gradation B with 6% asphalt and Figure 7 for gradation A with 6% asphalt. The corresponding bulk densities are shown in Figures 6 and 8. It is to be noted here that zero revolutions represents the standard kneading-compacted specimen. All of the seven test combinations performed upon the gradation A mixture resulted in an increase in stability followed by a decrease with higher numbers of revolutions. In comparison, only one of the four test combinations performed upon the gradation B mixture resulted in this type of stability curve. This might be explained by the fact that the gradation B mixture appears to be of poorer quality than the gradation A mixture, as indicated by the faster reduction in stability with increasing number of revolutions. The lack of an increase in stability for three cases of gyratory machine testing on the gradation B mixture leads one to postulate that the mixture would probably not gain stability under actual traffic loadings in the field and would fail early in its life due to loss of stability.

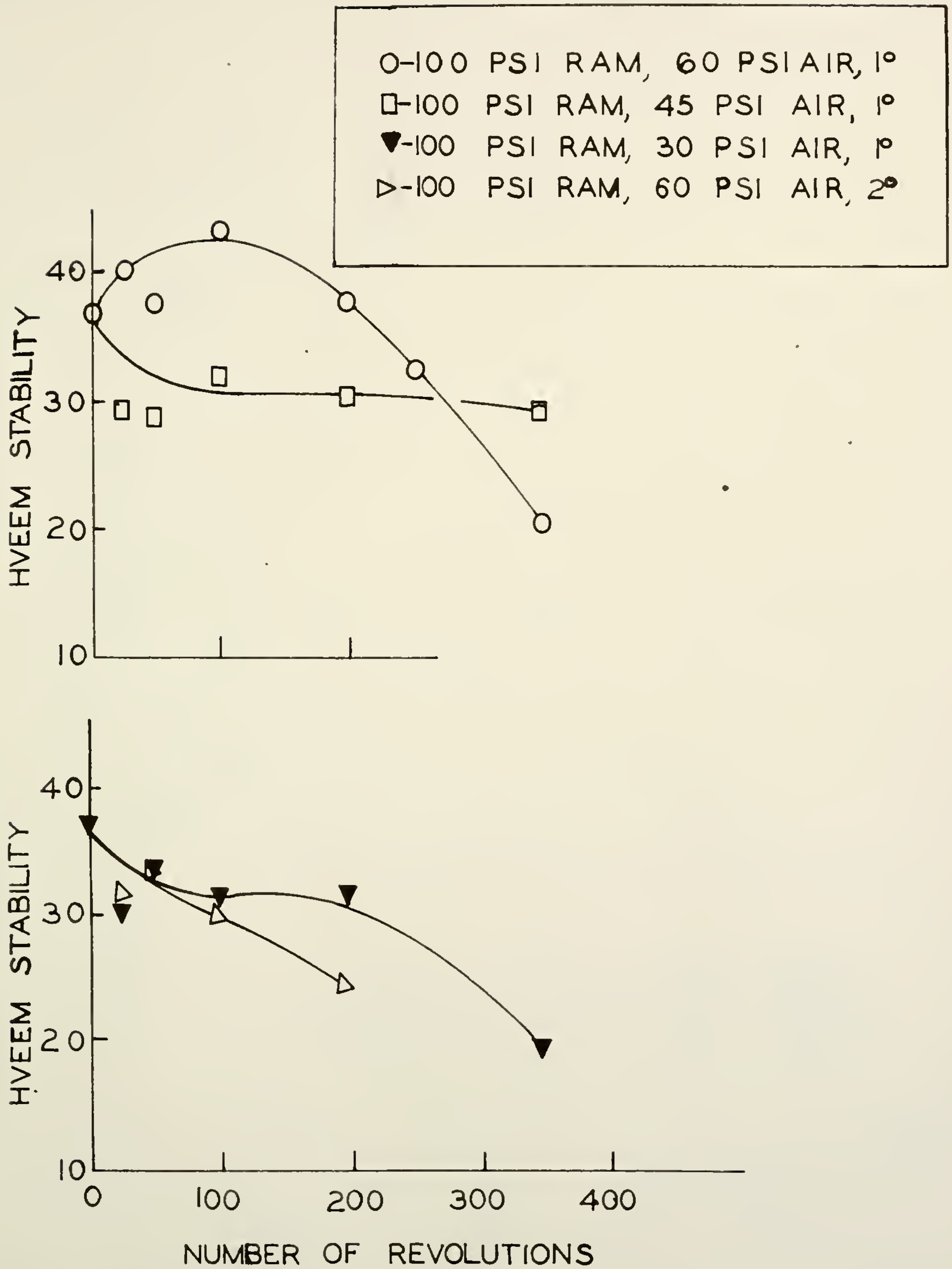

FIG. 5 HVEEM STABILITY VS. NO. OF REVOLUTIONS FOR VARIABLE GYRATORY TESTING

GRADATION B, 6% ASPHALT

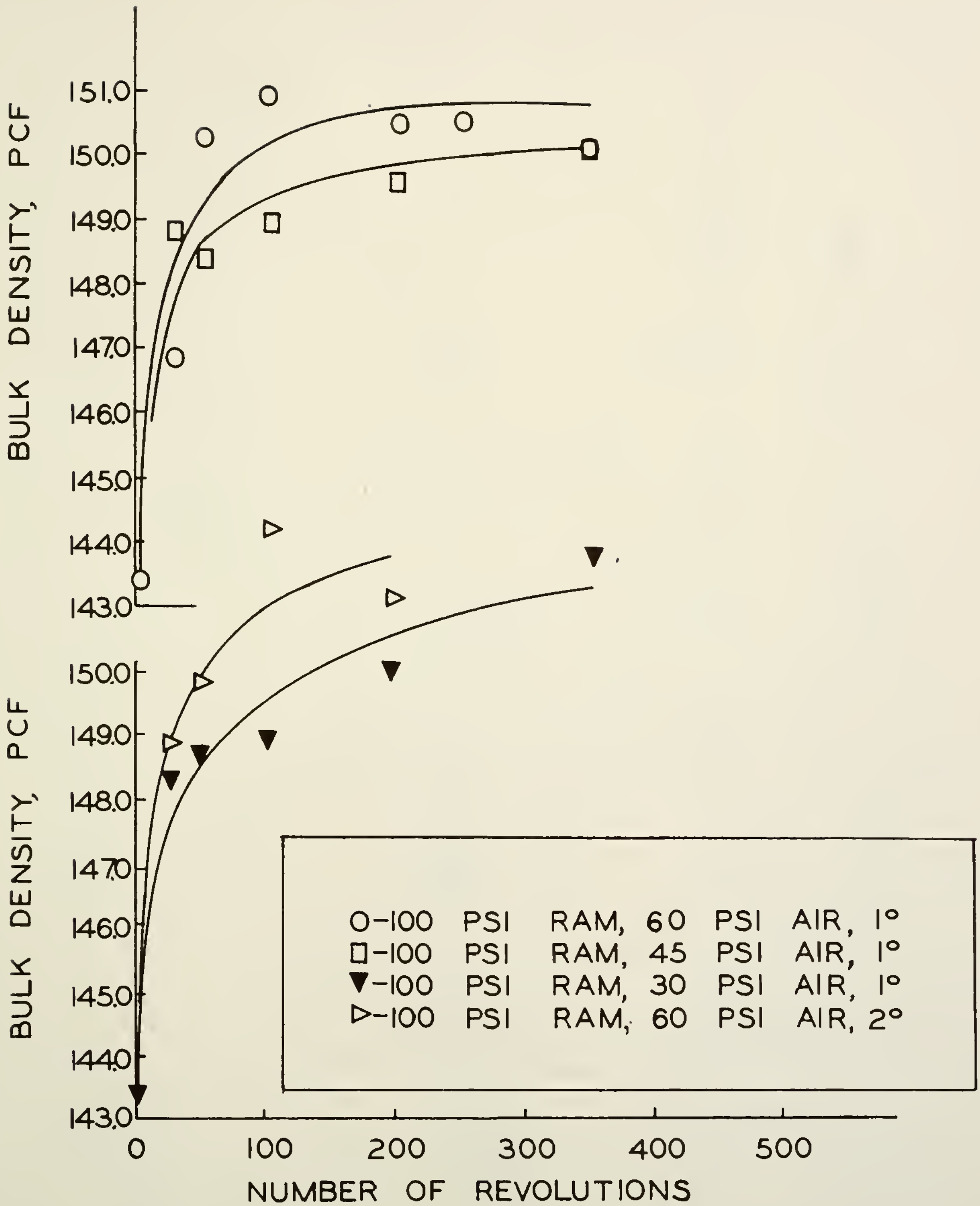

FIG. 6 BULK DENSITY VS. NO. OF REVOLUTIONS FOR VARIABLE GYRATORY TESTING

GRADATION B—6% ASPHALT

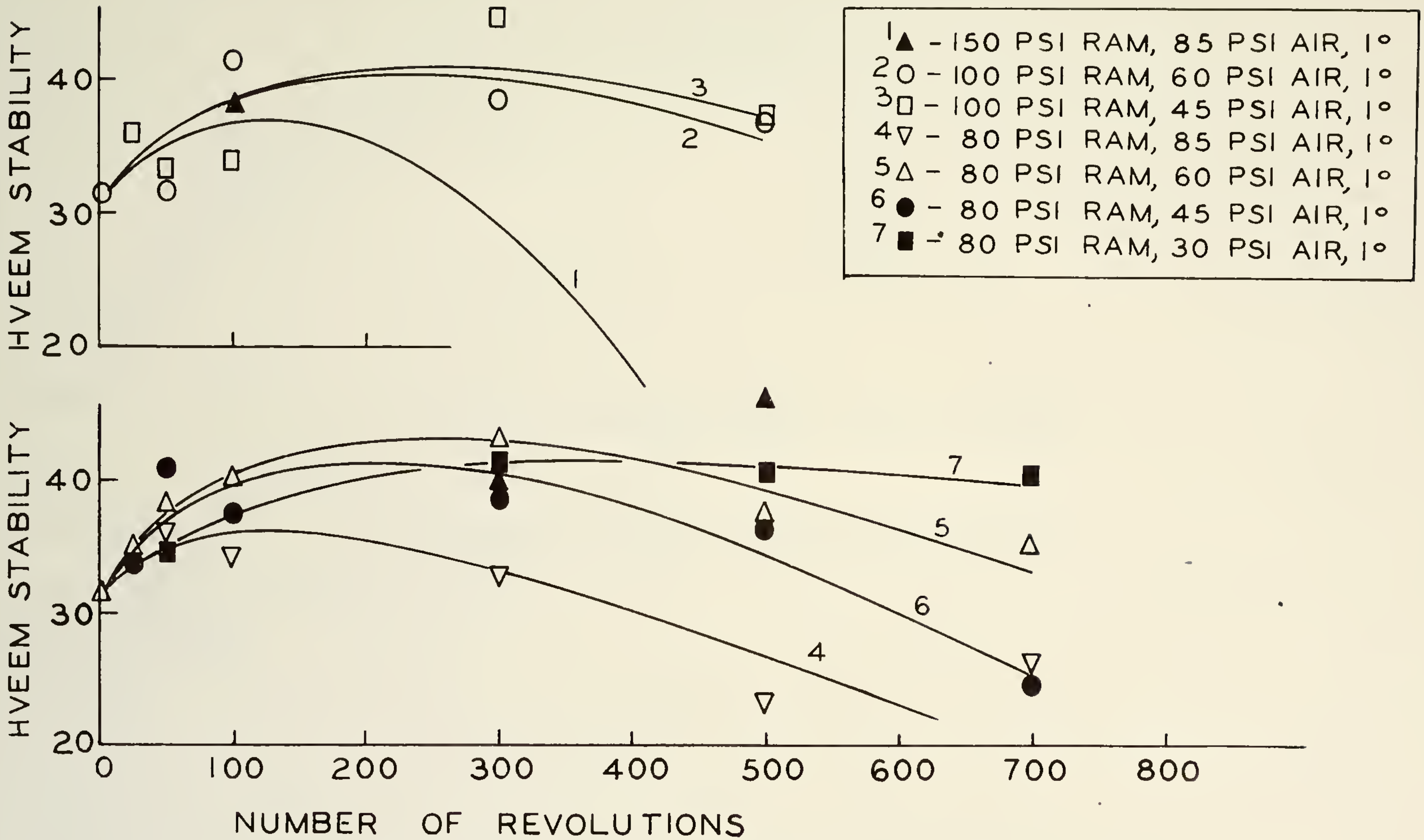

FIG. 7 HVEEM STABILITY VS. NO. REVOLUTIONS FOR VARIABLE GYRATORY TESTING

GRADATION A, 6 % ASPHALT

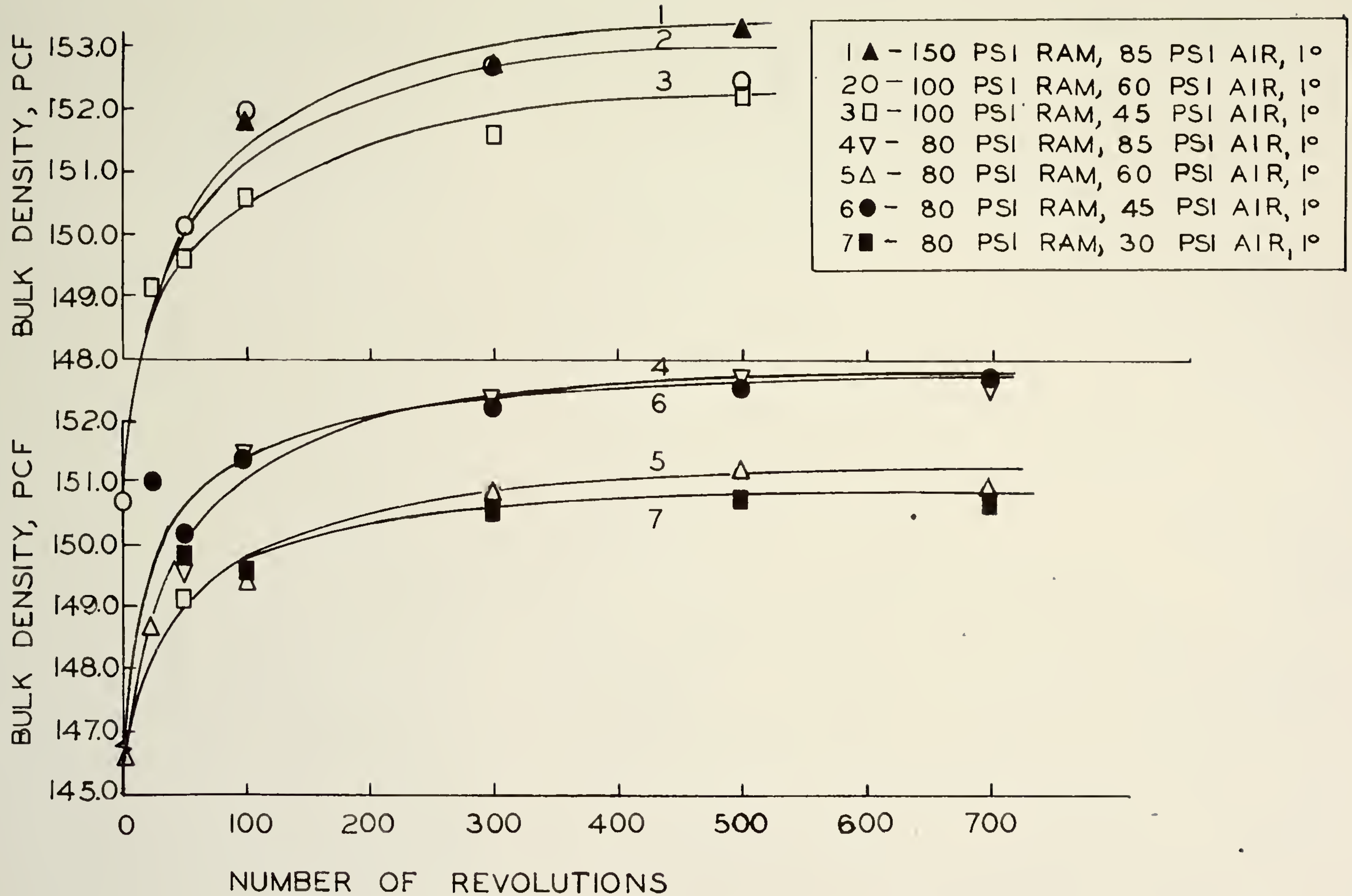

FIG. 8 BULK DENSITY VS. NO. OF REVOLUTIONS FOR VARIABLE GYRATORY TESTING, GRADATION A, 6% ASPHALT

Influence of Gyration Angle

Turning now to the effects of each gyratory machine variable, consider first the gyration angle. Tests on the gradation B mixture included one combination using a 2° gyration angle along with a 100 psi ram pressure and a 60 psi air pressure. The stability curve for this combination of variables can be compared to that of the combination of 100 psi ram pressure, 60 psi air pressure and 1° gyration angle (Figure 5). The 2° gyration angle caused a very significant decrease in stability as compared to that obtained with use of the 1° gyration angle. The stability curve with a 1° gyration angle increased during the first 100 revolutions and then decreased sharply, whereas the stability curve with 2° gyration angle decreased sharply from the start. Looking now at the bulk densities (Figure 6) the use of a larger gyration angle caused a greater rate of increase in density in the test specimens. These results lead one to consider the 2° gyration angle too great for use in laboratory testing of the type considered in this research study.

Influence of Ram Pressure

In assessing the effects of variable ram pressure for gyratory machine testing, Figures 7 and 8, it is concluded that higher ram pressures, in general, lower the maximum Hveem stability that is obtained. The maximum stability is also reached at a lower number of revolutions for the higher ram pressures and the rate of stability loss becomes somewhat greater. This conforms to what is expected because experience has shown that the higher the tire pressures and wheel loads on highway pavements, the sooner will failure conditions arise. The bulk density values for specimens tested at the higher ram pressures become greater, for other variables constant, which is what would be expected.

There is an inconsistency in the data in that the stability curve of 80 psi ram pressure, 45 psi air pressure and 1° gyration angle, in Figure 7, falls below the stability curve of 100 psi ram pressure, 45 psi air pressure and 1° gyration angle. This, therefore, is in direct conflict with the conclusions derived in the preceding paragraph. But this curve is also inconsistent when compared to the other curves of 80 psi ram pressure with different air pressures. Since there are two nonconformities for this particular curve, which incidentally holds true for bulk density values also (Figure 8), one is lead to consider that it might be brought into better agreement with the others by additional data collection.

It is difficult to relate the gyratory machine ram pressure to the tire pressure of vehicles on highway pavements without the benefit of a correlation between the results of testing on laboratory prepared specimens of bituminous concrete and the conditions brought out in the field pavement under traffic. When approaching this from the standpoint of trying to present evidence to show there is no connection between the two, the data in this research study give no basis upon which to do so. Therefore it is not unreasonable to postulate that the gyratory testing machine ram pressure is related to tire pressure in a simulated traffic testing procedure.

Influence of Upper Roller Air Pressure

The upper roller air pressure of the gyratory testing machine was the principal variable studied. Before it could be used in a simulated traffic testing procedure, it was imperative to study the effects it would have upon a test specimen and how it might best be used in such a procedure.

When using the air-filled roller in the operation of the gyratory machine, the gyration angle varies with the pressure set in the air cell. Setting an initial gyration angle is accomplished by placing the fixed-roller in the machine and varying the elevation of the bottom roller until the desired gyration angle is reached. It was observed that a variation in air pressure caused a difference in the initial angle recorded on the gyrograph. Figure 10 shows that at a 30 psi air pressure the initial gyrograph angle recorded was approximately half of the 1^{o} gyration angle set by use of the fixed roller, whereas at air pressures between 45 psi and 85 psi, the initial gyrograph angle was closer to 1^{o}. This shows that, for the test conditions of this study, increasing the upper roller air pressure above 45 psi had little effect on changing the initial gyrograph angle recorded as compared to that obtained when the air pressure was increased from 30 psi to 45 psi. Referring to Figure 9, the same characteristic is noticed in that increasing the upper roller air pressure above 45 psi had little effect on changing the % axial deformation of test specimens.

Some clarification is necessary here in regard to the relation between the gyration angle described by the rollers and the angle recorded by the gyrograph. The angle recorded by the gyrograph may be larger than the angle set by the two rollers because rotation can occur about a line through the points of contact of the two rollers on the flange. This type of movement therefore is an indication of the strength change of the specimen being tested, for as the specimen loses strength it offers less lateral resistance to the gyrating action of the rollers, allowing greater rotation about the line through the two rollers.

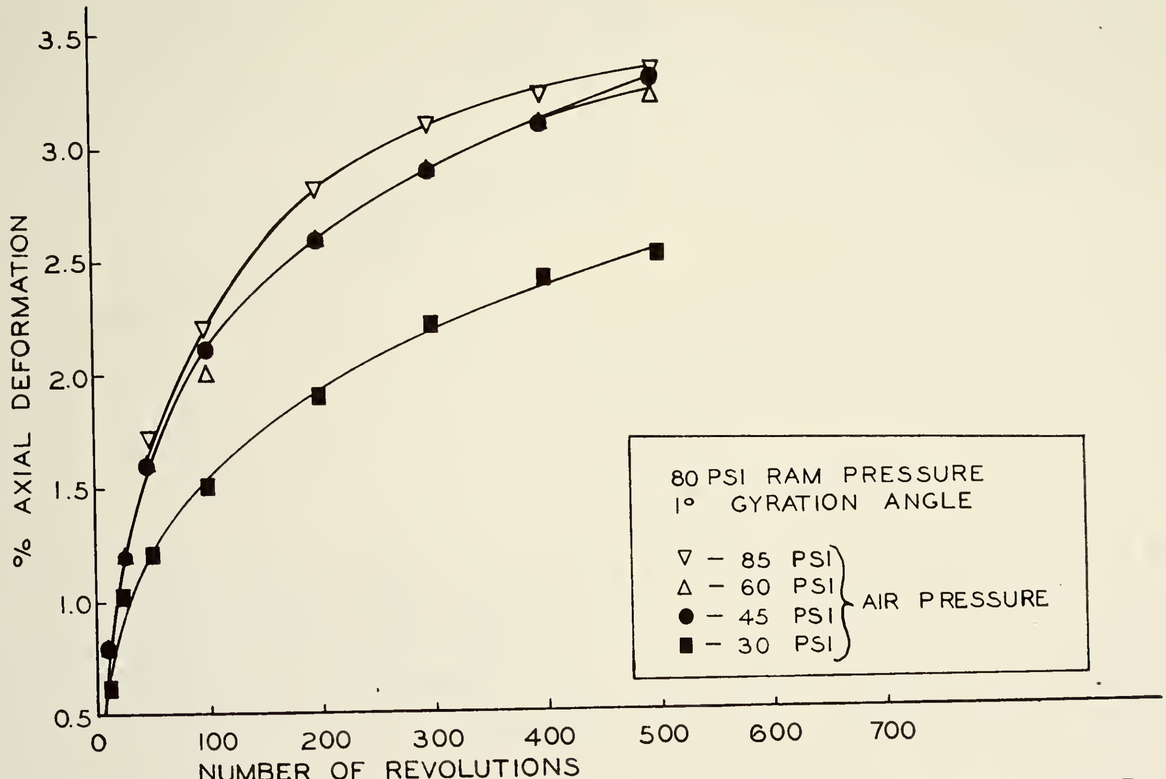

FIG. 9 % AXIAL DEFORMATION VS. NO. REVOLUTIONS FOR VARIABLE AIR PRESSURE, GRADATION A – 6% ASPHALT

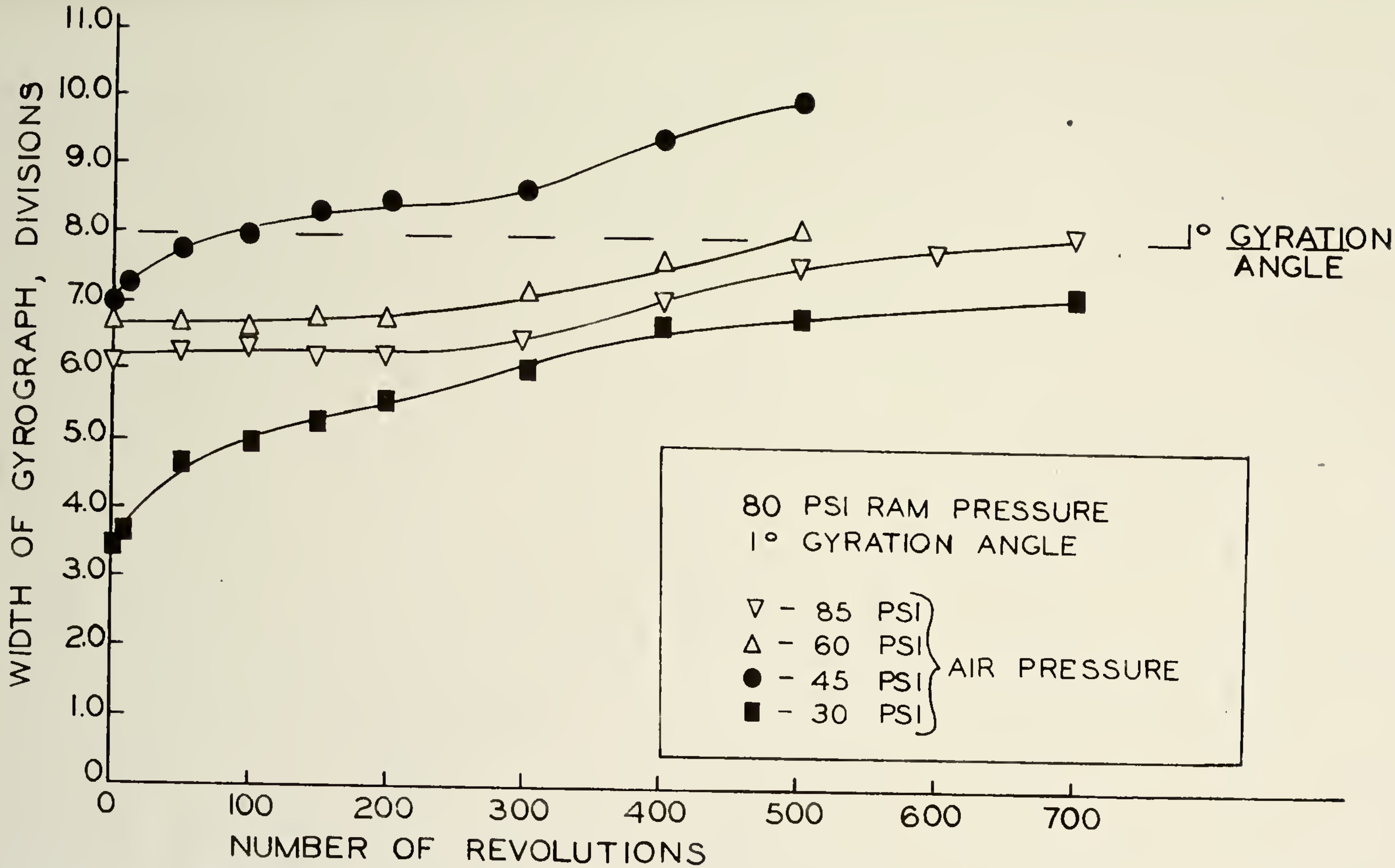

FIG. 10 WIDTH OF GYROGRAPH VS NO. OF REVOLUTIONS FOR VARIABLE AIR PRESSURE, GRADATION A, 6% ASPHALT

This research study has found the gyrograph recording to have a poor sensitivity to the change in stability of the test specimen. It does not give a reliable indication of whether the specimen strength is increasing or decreasing, nor the rate of such change. Typical measurements of the recorded gyrograph angle (width of gyrograph) are shown in Figure 10. When compared to the change in stability with number of revolutions, Figure 7, they seem to indicate, by an increase in the angle recorded, approximately where stability begins to decrease. This indication, however, did not hold true for all test specimens. Changes in gyration angle recorded on the gyrograph are also difficult to determine because any change that does occur is gradual.

Returning again to effects of the upper roller air pressure, the data show that as this pressure is increased the compactive effort applied to the test specimen also increases. For other variables constant, it is observed that an increase in air pressure lowers the maximum stability that is obtained during gyratory testing and lowers the range of revolutions over which the test specimen performs satisfactorily if an arbitrary minimum Hveem stability value is selected (refer to Figure 7). It is reasonable to assume, therefore, that the higher the upper roller air pressure the more influencial it is in breaking down the lateral showing resistance and, thus, stability of the specimen.

Figure 9 shows that, up to 500 revolutions of gyratory testing at 80 psi ram pressure and 1° gyration angle, there is little increase in percent axial deformation as the upper roller air pressure is increased from 45 to 85 psi. It appears that higher values of air pressure have a greater effect on change in Hveem stability of test specimens than on change in their axial deformation or compactive densification.

A conclusion derived from the preceding paragraphs is that the higher values of upper roller air pressure used in this study, 45 to 85 psi, are applicable for use in a traffic testing procedure. Pressures at this level cause breakdown of strength in the laboratory specimen which appears to be similar to that of the actual highway pavement and in a reasonable length of testing time. Increasing the air pressure lowers the number of revolutions through which the specimen will perform satisfactorily if an arbitrary minimum stability is selected. In this respect its effect is similar to that of the ram pressure variable.

Although tests involving fixed roller operation were not performed as part of this research study, information on such operation can be found in reference material (2, 5, 9). The fixed-strain method of fixed roller operation appears to "force" the test specimen unduly. It is felt that the air-filled roller is better suited to a traffic testing procedure than operation with the fixed roller because the roller position can vary when resistance of the specimen varies and thus the effect on the specimen is made dependent upon specimen characteristics developed. This is a realistic approach to simulated field conditions. At high pressures, operation with the air-filled roller does seem to approach conditions produced by the fixed roller. So caution must be exercised to prevent use of very high values that would "force" the specimen unduly.

As a check on variation in pressure on the upper roller, two test specimens were subjected to gyratory machine testing with the oil-filled roller placed in the machine. Because of trapped air within the oil-chamber, pressures obtained (not reported in this paper) were not correct but they indicated that while specimen stability was decreasing the pressure on the upper roller was also decreasing. There is agreement between this result and the belief that the specimen offers less lateral resistance to the gyrating action as its strength is decreasing.

The results of this part of the research study show that it is reasonable to carry out a simulated traffic testing procedure with the air-filled roller in the gyratory testing machine and that different values of air pressure might be utilized to represent various types of traffic loadings. The number of revolutions through which the mixture maintained satisfactory stability would be considered the criterion for performance. The purpose of utilizing different air pressures would be to evaluate the performance characteristics of a paving material under varying traffic loadings. The scope of a procedure such as this would be extensive, particularly when a field correlation study was involved. In this respect, such a procedure might be considered unrealistic. In contrast, a procedure for simulated traffic testing utilizing only one value for each variable would simplify the testing. With a set procedure such as this, many bituminous mixture types could be tested for a comparative evaluation of performance in service. A field correlation study might then be performed to determine what the number of revolutions represented in terms of service life.

With the above concepts in mind, the remaining portions of the results describe operation of the gyratory testing machine as a traffic simulating device utilizing set values for each variable.

Traffic Testing with the Gyratory Machine

The results of the investigation of gyratory testing machine variables furnished a foundation on which the remaining portion of this research study could be based. This involved the selection of some combination of gyratory machine variables for use in a test procedure simulating the action of traffic on bituminous concrete in highway pavements. The decision was made to use the combination of 80 psi ram pressure, 60 psi upper roller air pressure and 1° gyration angle as being reasonably representative of normal traffic loading on actual pavement surfaces. This loading system was then used for testing bituminous mixtures compacted at variable asphalt content. The purpose was to determine the manner in which the gyratory machine used as a traffic simulating device would evaluate the effects of asphalt content and aggregate gradation on mixture performance.

Influence of Variable Asphalt Content

In this study the testing of bituminous mixtures of variable asphalt content showed that, with aggregate gradation constant, the higher the asphalt content the lower was the maximum Hveem stability reached by a test specimen during the simulated traffic testing procedure. Higher asphalt content specimens also fell below minimum Hveem stability criteria at a lower number of revolutions. This is shown in Figures 11 and 13 by a Hveem stability vs. number of revolutions relationship for gradation A and D mixtures.

Figures 12 and 14 show corresponding bulk density relationships for these mixtures. The A and B portions of these figures show the bulk

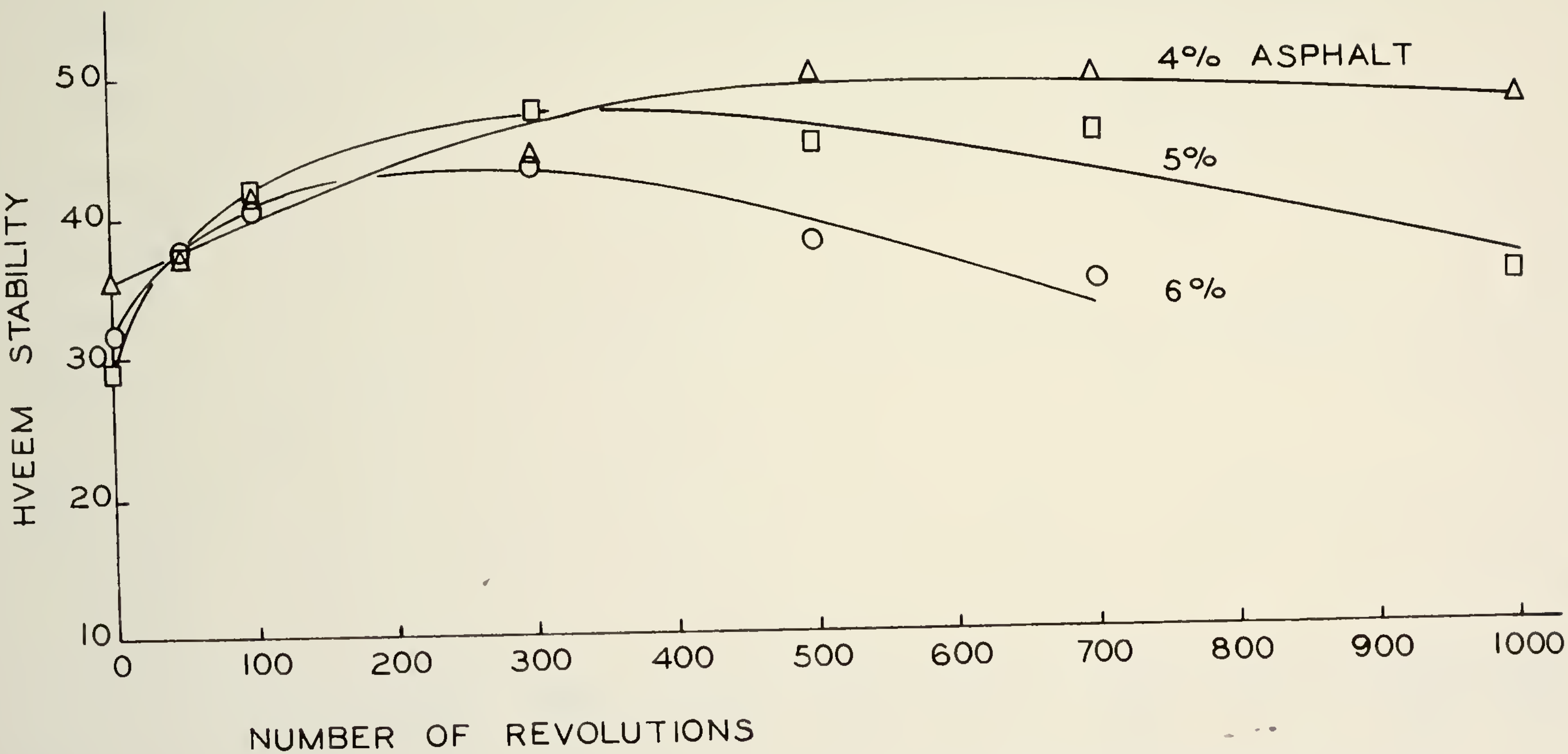

FIG. 11 HVEEM STABILITY VS NO. OF REVOLUTIONS FOR VARYING ASPHALT CONTENT
GRADATION A'– 80 PSI RAM PRESSURE, 60 PSI AIR PRESSURE, 1° GYRATION ANGLE

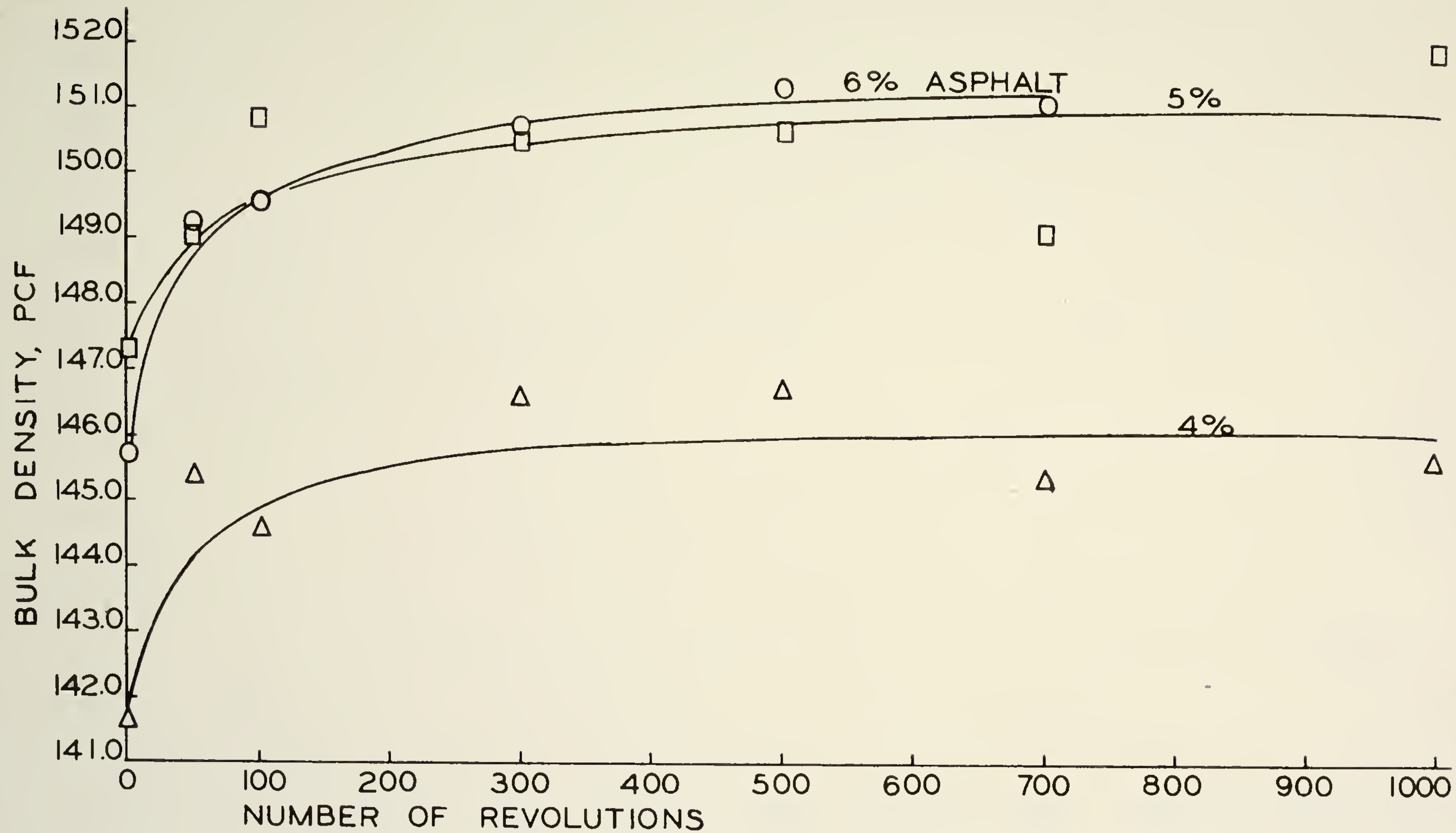

FIG. 12A BULK DENSITY VS. NO. OF REVOLUTIONS FOR VARYING ASPHALT CONTENT

GRADATION A — 80 PSI RAM PRESSURE, 60 PSI AIR PRESSURE, 1° GYRATION ANGLE

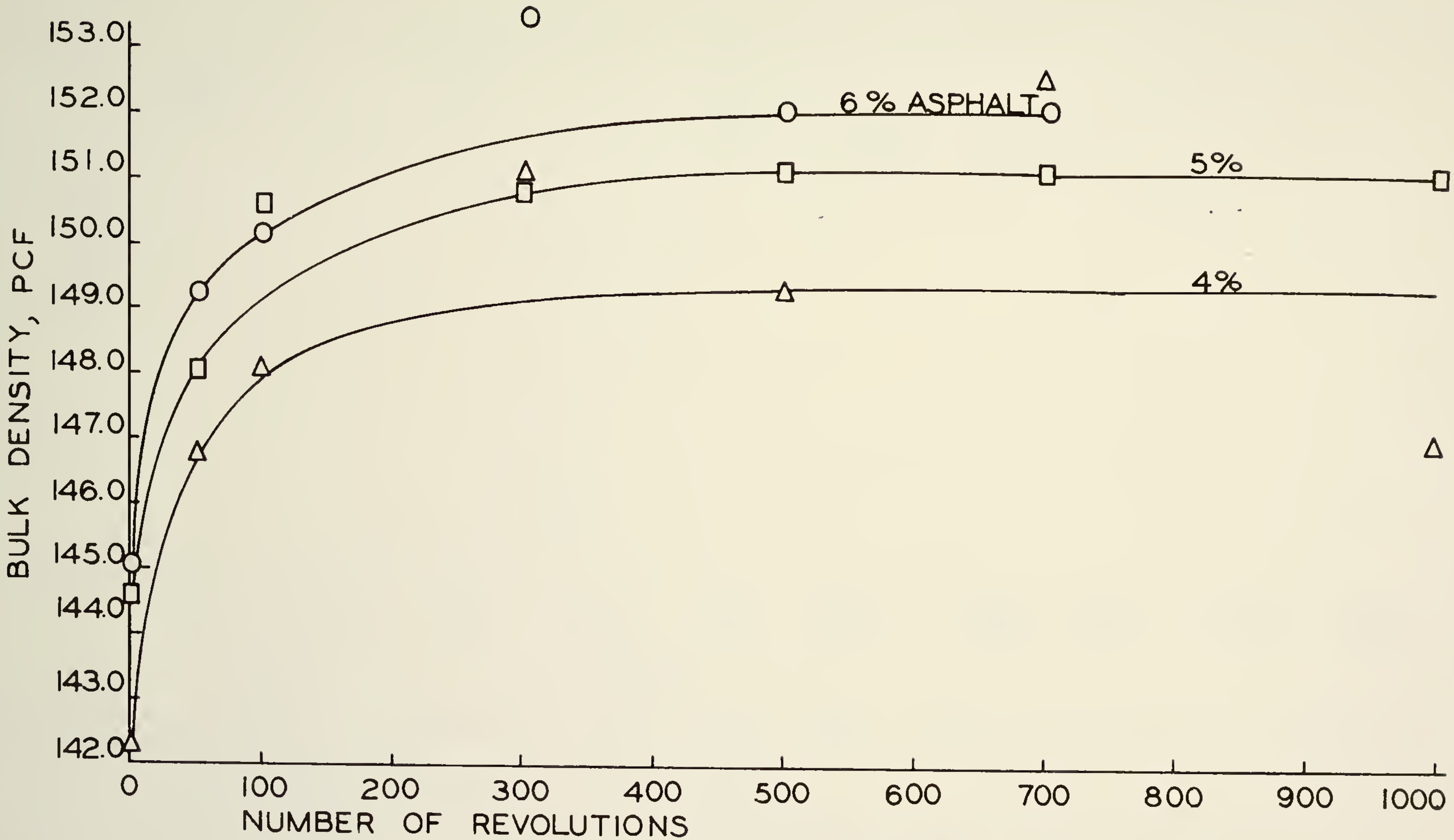

FIG. 12B BULK DENSITY (BASED ON SPECIMEN HEIGHT) VS NO. OF REVOLUTIONS FOR VARYING ASPHALT CONTENT

GRADATION A—80 PSI RAM PRESSURE, 60 PSI AIR PRESSURE, 1° GYRATION ANGLE

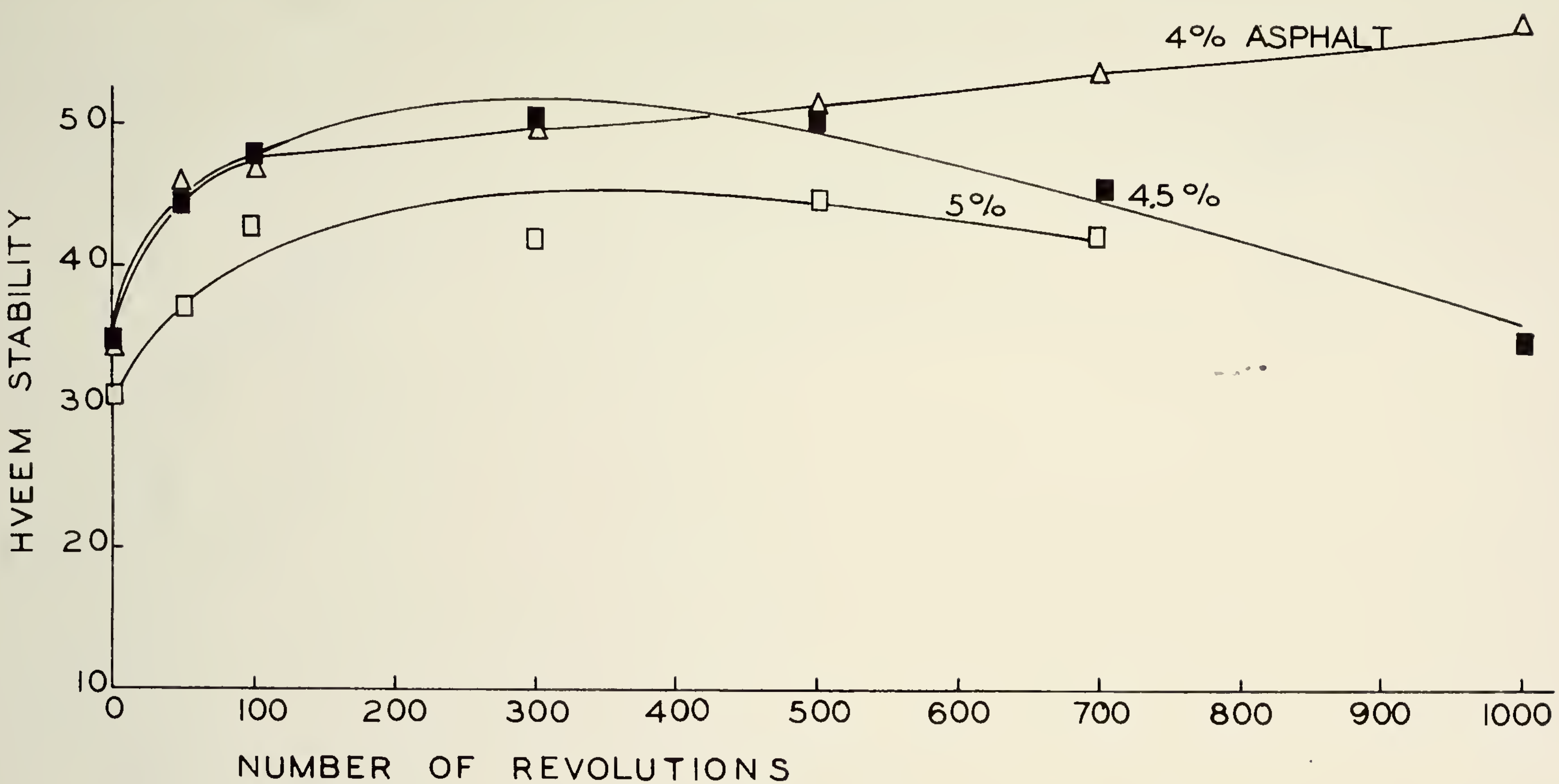

FIG. 13 HVEEM STABILITY VS NO. OF REVOLUTIONS FOR VARYING ASPHALT CONTENT

GRADATION D—80 PSI RAM PRESSURE, 60 PSI AIR PRESSURE, 1° GYRATION ANGLE

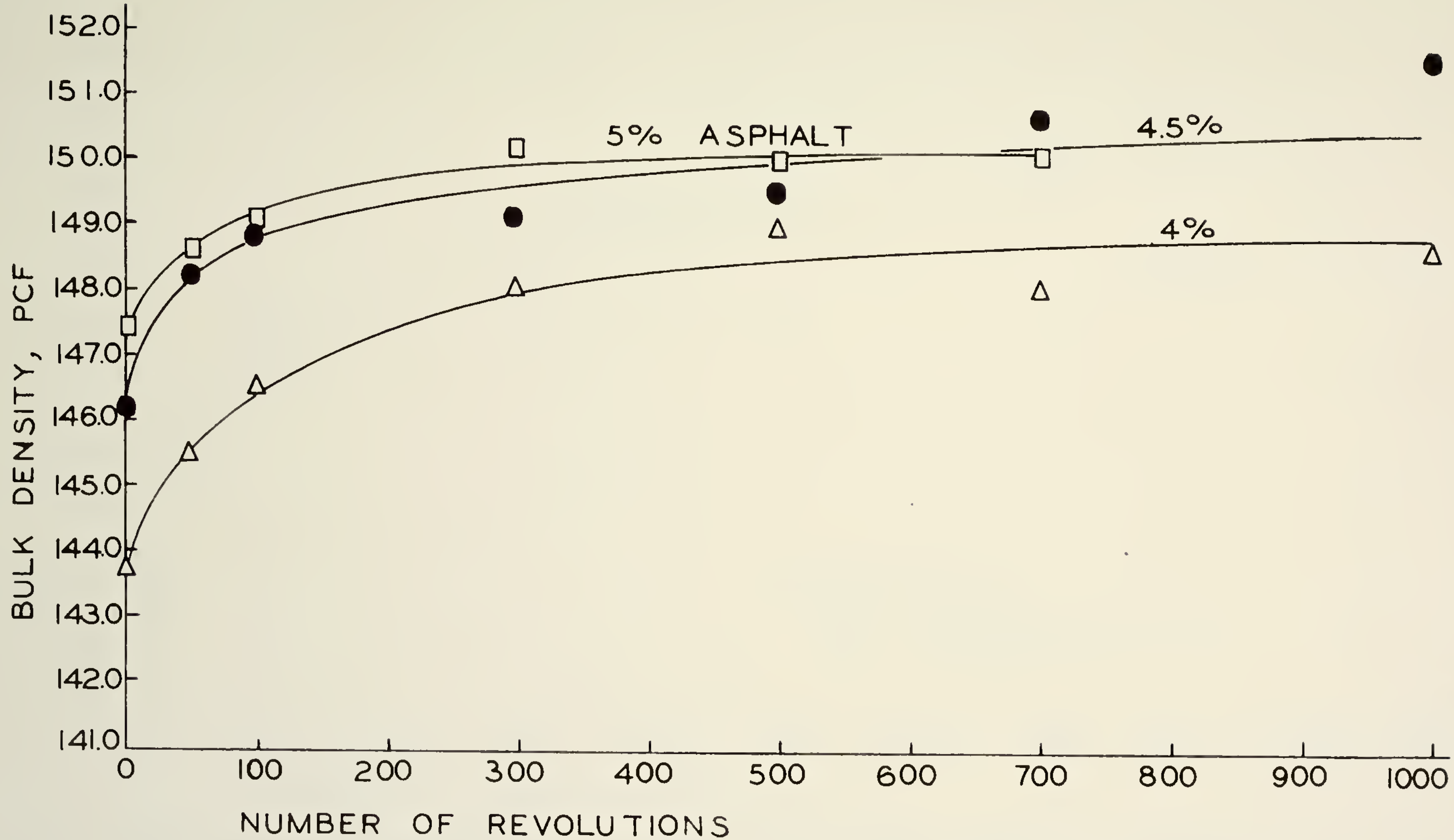

FIG. 14A BULK DENSITY VS. NO. OF REVOLUTIONS FOR VARYING ASPHALT CONTENT
GRADATION D — 80 PSI RAM PRESSURE, 60 PSI AIR PRESSURE, 1° GYRATION ANGLE

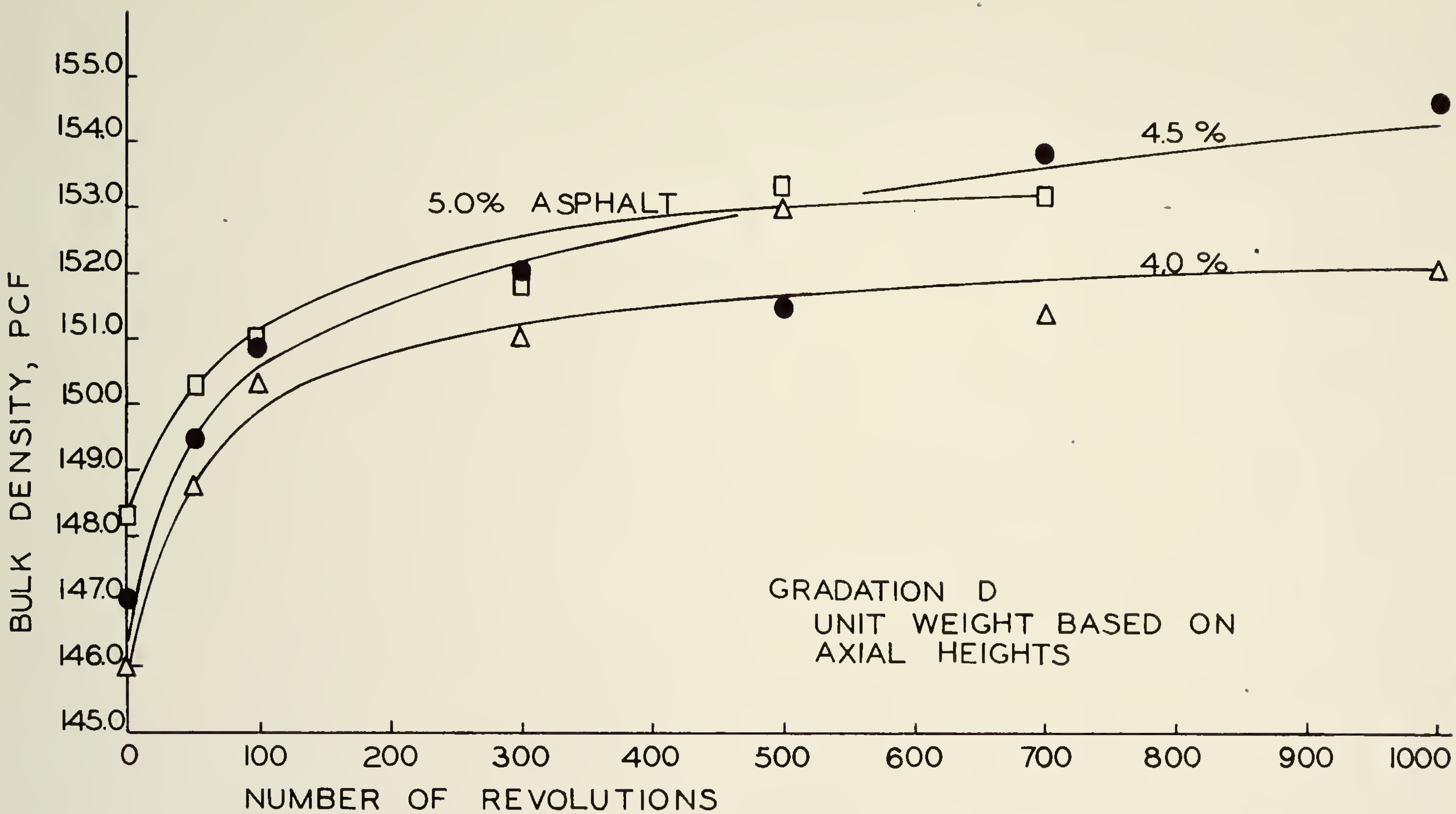

FIG. 14B BULK DENSITY (BASED ON SPECIMEN HEIGHT) VS. NO. OF REVOLUTIONS FOR VARYING ASPHALT CONTENT

GRADATION D – 80 PSI RAM PRESSURE, 60 PSI AIR PRESSURE, 1° GYRATION ANGLE densities based on specimen weight in air and water and on axial height measurements, respectfully. Those based on axial height measurements are calculated on the basis that the rigid mold around the specimen allows deformation in only the axial direction. It is observed that density values are lower when computed on the basis of specimen weights in water. It is believed that this is caused by swelling of the specimens when soaked in water for the 24 hours prior to weight determinations in water and by expansion of the specimen with release of pressure when removed from the test mold. It was found in a previous research study (2) that the Hveem stabilometer test increases specimen density, at least for some specimens. Since the water displacement bulk density in this study was determined after the stabilometer test, it is possible that this factor influenced differences between density values determined by the two methods, also. The major increase in bulk density of test specimens occurred during the early number of revolutions. The test specimens studied here continued to have a Hveem stability greater than the accepted minimum for a significant number of revolutions after the near maximum density was reached early in the test, with this number becoming larger as the asphalt content decreased.

Another characteristic of the test specimen that might be looked at is content of air voids and its variaton during gyratory machine testing and with asphalt content. Table 4 shows results of calculations for percent air voids of the gradation A mixtures. The maximum bulk density of the mixtures is based on use of bulk specific gravity for the aggregate portion and assumes no asphalt absorption by the aggregate. The actual bulk density of test specimens are those computed from axial height data.

TABLE 4

PERCENT AIR VOIDS FOR GRADATION A MIXTURES

No. of Revolutions	Asphalt Content, %	Maximum Specimen Bulk Density	Actual Specimen Bulk Density	% Air Voids
0	6	150.9	145.0	+ 3.9
50	6	150.9	149.3	+ 1.1
100	6	150.9	150.1	+ 0.5
300	6	150.9	153.5	- 1.7
500	6	150.9	152.1	- 0.8
700	6	150.9	152.0	- 0.7
0	5	152.8	144.6	+ 5.3
50	5	152.8	148.1	+ 3.1
100	5	152.8	150.5	+ 1.5
300	5	152.8	150.8	+ 1.3
500	5	152.8	151.1	+ 1.1
700	5	152.8	151.1	+ 1.1
1000	5	152.8	151.1	+ 1.1
0	4	154.9	142.3	+ 8.0
50	4	154.9	146.8	+ 5.2
100	4	154.9	148.1	+ 4.4
300	4	154.9	151.0	+ 2.5
500	4	154.9	149.3	+ 3.6
700	4	154.9	152.5	+ 1.6
1000	4	154.9	147.0	+ 5.1

The data of Table 4 indicate that the mixture with 6% asphalt has a negative percent air voids after 300 revolutions in the gyratory machine. Since there cannot be a negative percent air voids, two things can happen which would explain why the negative value was obtained. First, it is quite likely that a portion of the asphalt has been absorbed into the aggregate, either during initial mixing of the mixture and/or during testing in the gyratory machine. Secondly, asphalt could be squeezed out of the specimen as gyratory testing consolidated it, a condition referred to as "flushing". The second was found to be true. Flushing occurred for test specimens of fairly high asphalt content, tested at the higher number of revolutions. Simulated traffic testing in the gyratory machine reduced the air void content appreciably during the first 100 revolutions for those test specimens represented by this table. Reduction of air voids to a near zero quantity is considered to be one of the main causes of stability failures in bituminous concrete. Consequently a test procedure such as this appears to offer valuable information on variation of this property.

These results indicate that gyratory machine simulated traffic testing procedure can serve as a basis for determining a range of asphalt content for which a mixture of a particular aggregate gradation can be expected to perform satisfactorily in service. A correlation study between laboratory test performance and field performance of bituminous mixtures would be helpful in determining what "satisfactory performance" is represented by in the laboratory procedure of gyratory machine simulated traffic testing.

Figure 15 shows width of gyrograph (angle of gyration) vs. number of revolutions for two specimens at each asphalt content for the gradataion A mixtures. In general, the gyrograph records a greater angle of gyration for the mixtures of higher asphalt content. The gyrograph also indicates that the greater the asphalt content of the test specimen, the greater will be the increase in angle of gyration during testing. The greater change in angle of gyration indicates a greater rate of change in stability of the test specimen. Again, as described earlier, the increase in gyration angle is difficult to observe on the gyrograph. The gyrograph shows some promise as an indicator of change in stability of a test specimen, and refinement of this measurement might increase its reliability as an indicator of this kind.

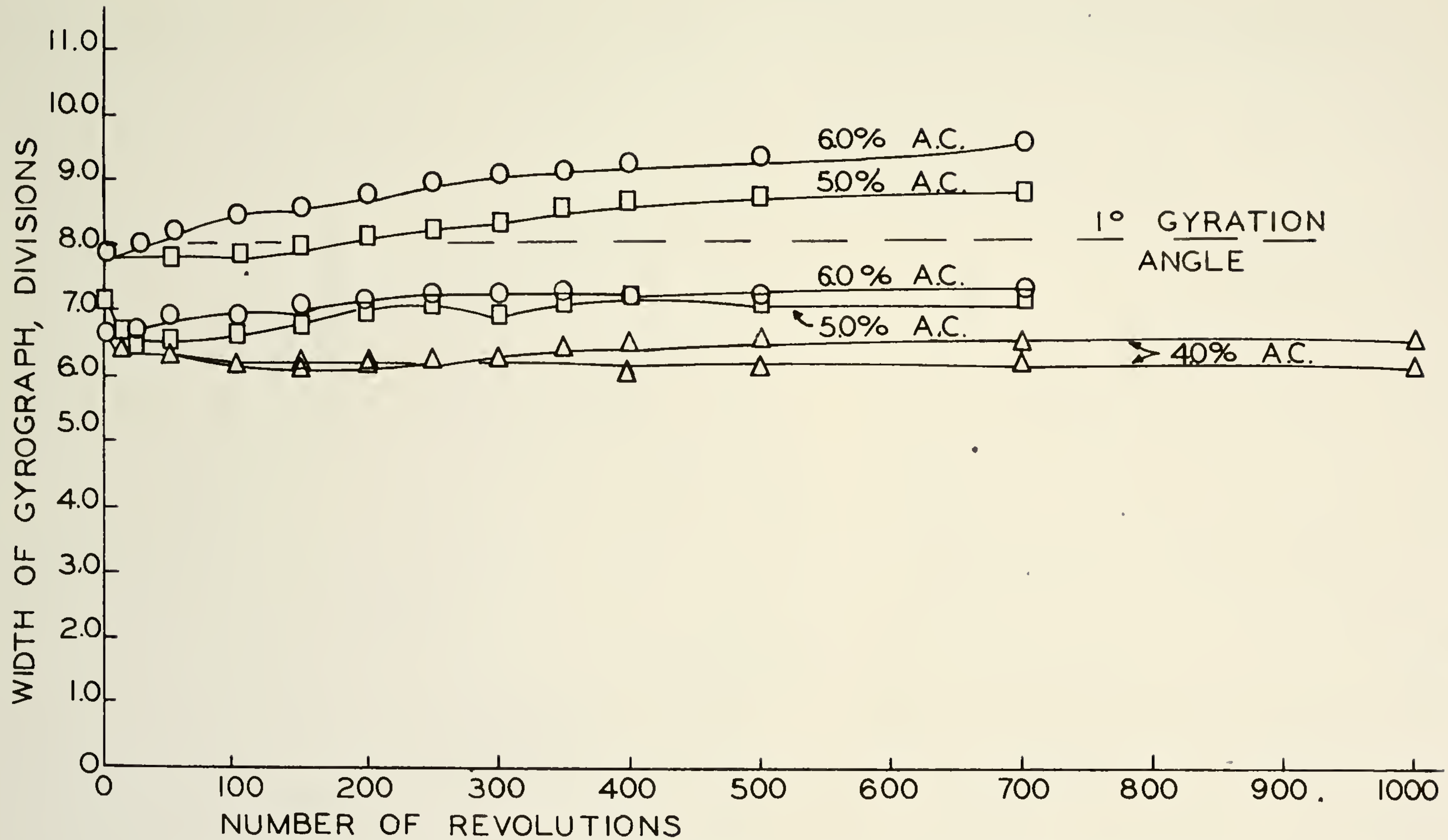

FIG. 15 WIDTH OF GYROGRAPH VS NO. OF REVOLUTIONS FOR VARIABLE ASPHALT CONTENT
GRADATION A— 80 PSI RAM PRESSURE, 60 PSI AIR PRESSURE, 1° GYRATION ANGLE

There is an indication that, in general, mixtures of lower asphalt content have a greater rate of axial deformation at low number of revolutions and a smaller rate of axial deformation as high number of revolutions are reached as compared to higher asphalt content mixtures. This can be observed in Figures 16 and 17 for the gradation A and D mixtures. It might be interpreted that large quantities of asphalt (low air void content) assist in destroying the structural stability of the aggregate portion by a "lubricating" action, resulting in additional consolidation of the test specimen. The recordings of axial deformation from the gyratory machine show that density was always increasing during testing of specimens in this study.

Performance vs. Aggregate Gradation

The simulated traffic testing of the mixtures of different aggregate gradation at the same asphalt content showed quite clearly that a difference in performance could be expected from them. For the same asphalt content, the gradation B mixture of Figure 5 lost more stability, at a more rapid rate, than the gradation A mixture of Figure 11. In Figure 18 is shown Hveem stability and bulk density vs. number of revolutions for the gradation H (high sand content) mixture of 6% asphalt. This mixture had an initial kneading compactor stability that might be considered too low to be acceptable, but testing in the gyratory machine increased this stability to an amount considered acceptable before a decrease brought it again to an unacceptable range. Unacceptable stability for this mixture also occurred sooner than that of the gradation A mixture. Both mixtures satisfy the Indiana specifications for type-B surface course materials.

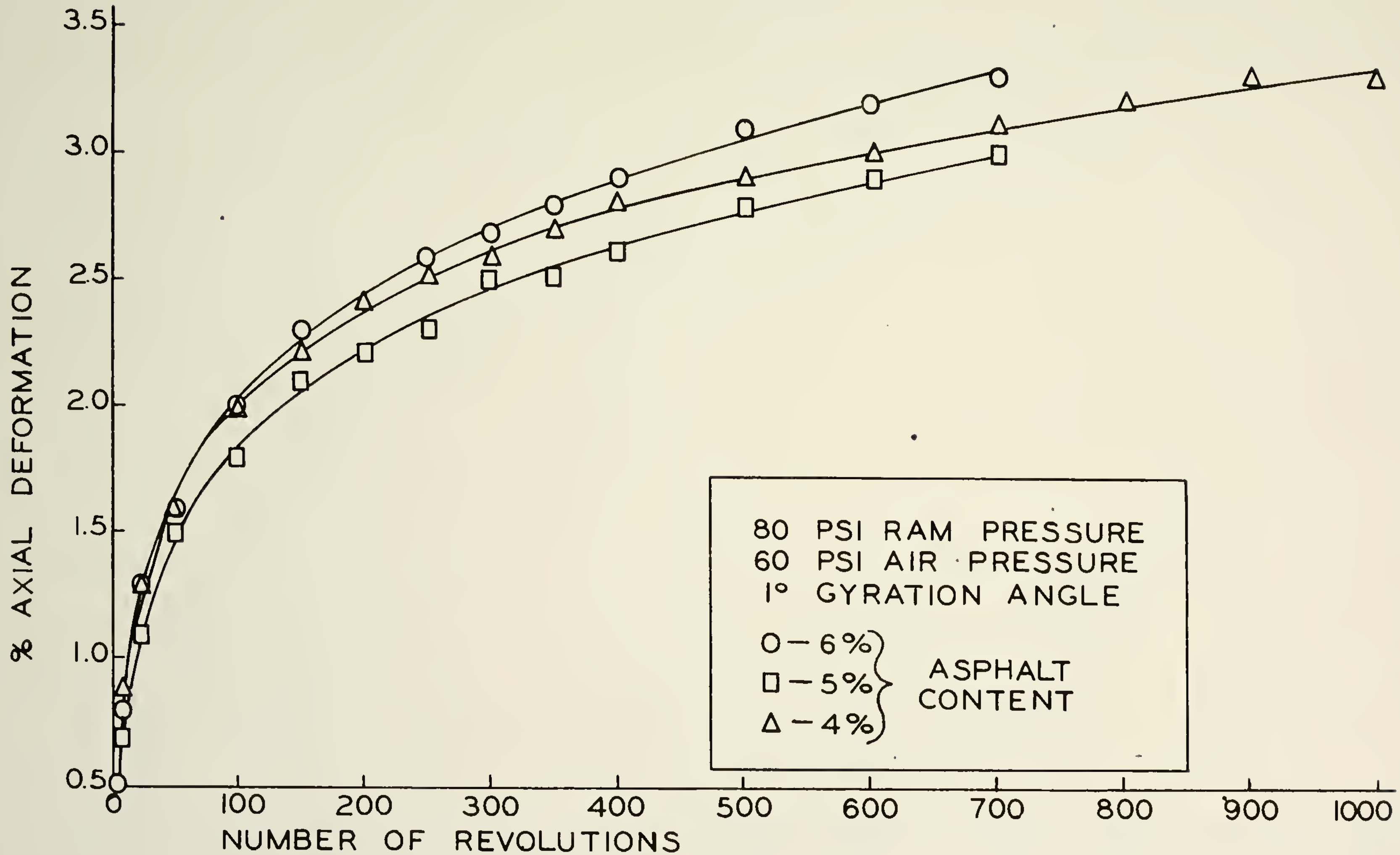

FIG. 16 % AXIAL DEFORMATION VS. NO. OF REVOLUTIONS FOR VARYING ASPHALT CONTENT, GRADATION A

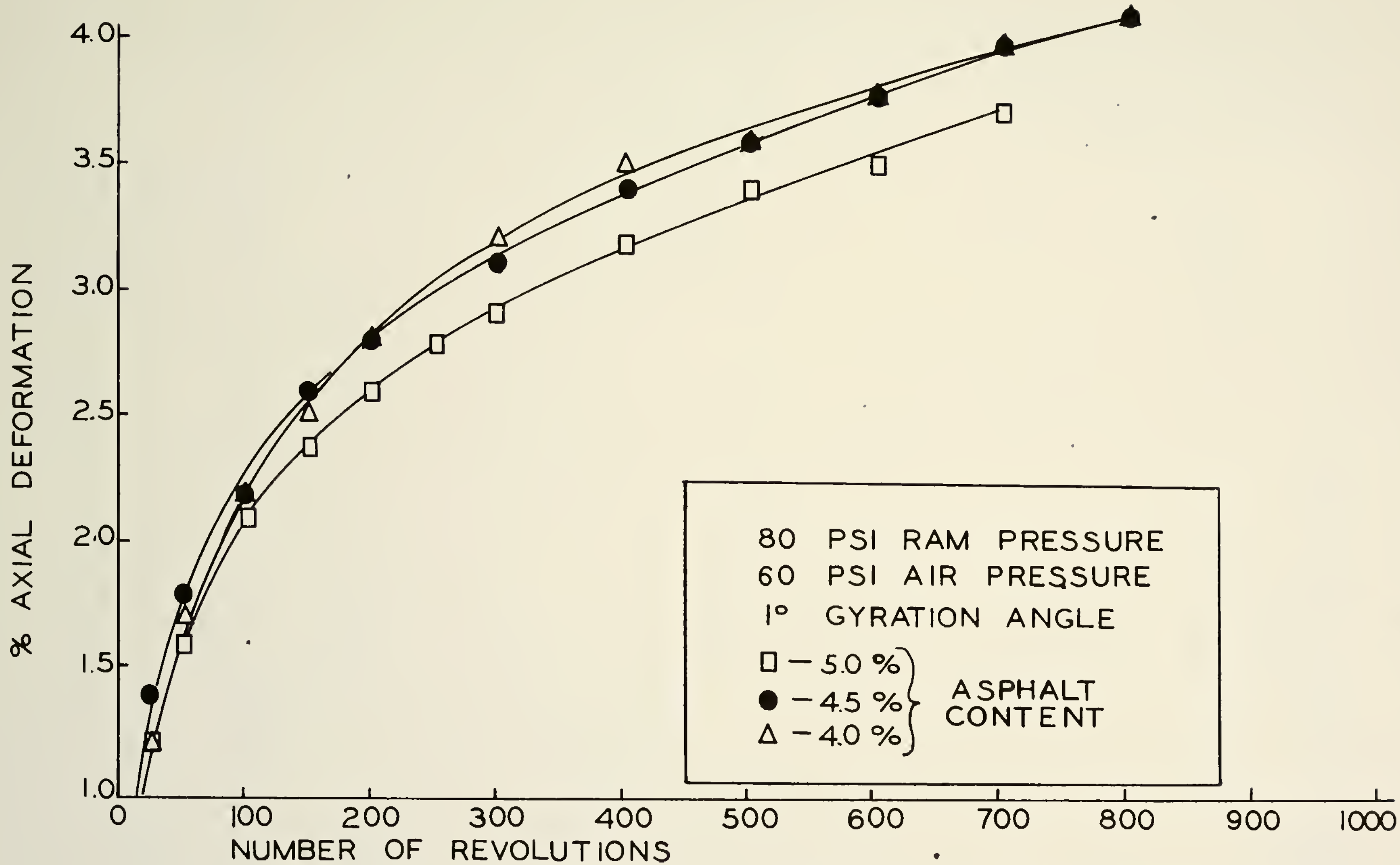

FIG. 17 % AXIAL DEFORMATION VS. NO. OF REVOLUTIONS FOR VARYING ASPHALT CONTENT, GRADATION D

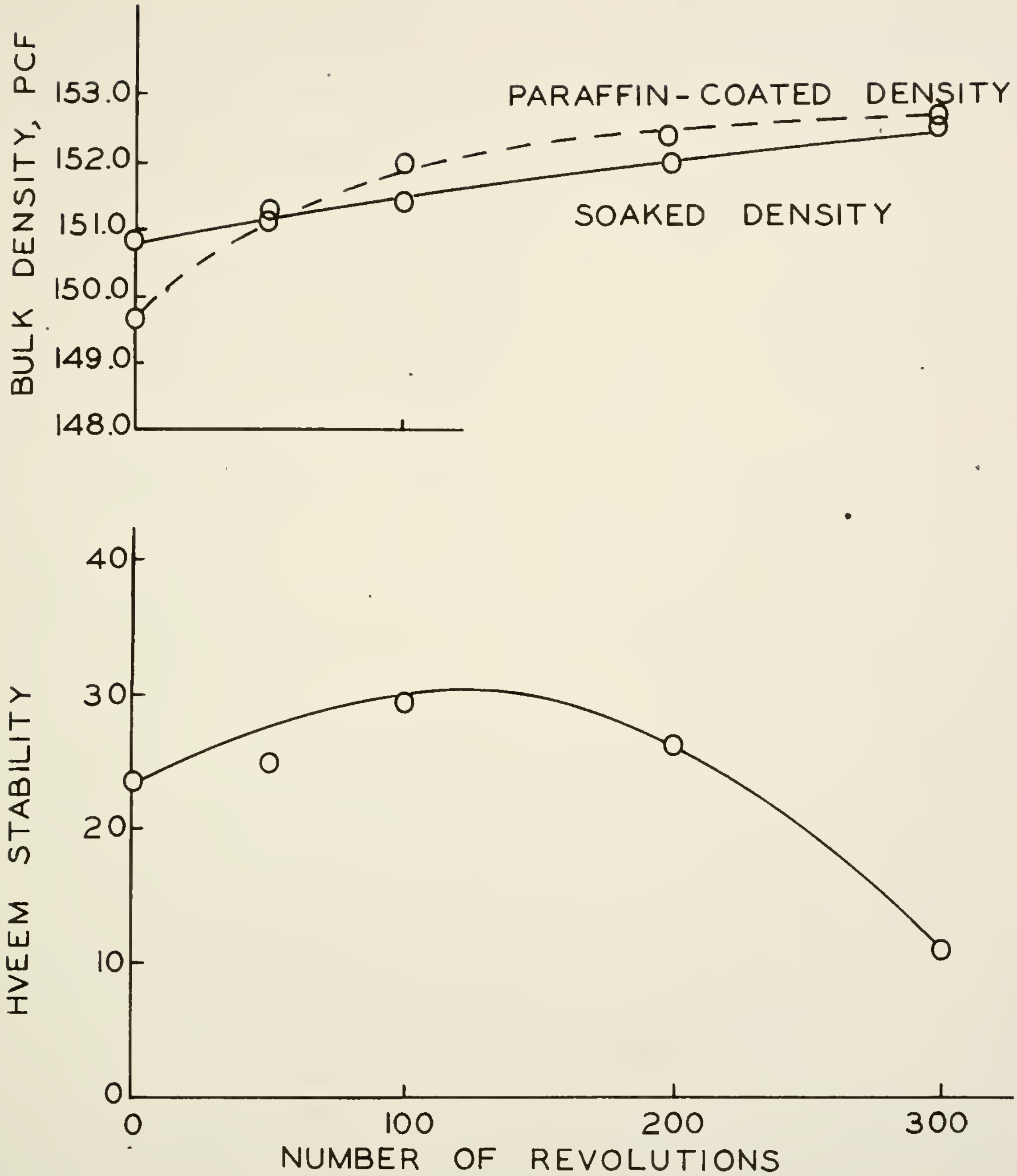

FIG. 18 HVEEM STABILITY AND BULK DENSITY VS NO. OF REVOLUTIONS

GRADATION H - 6 % ASPHALT, 80 PSI RAM PRESSURE, 60 PSI AIR PRESSURE, 1° GYRATION ANGLE

The point to be emphasized here is that the Hveem stability alone does not give a reliable indication of how a mixture will perform in the gyratory machine. Some mixtures may have a satisfactory stability when initially compacted, but when subjected to simulated traffic testing they may lose stability and fail very rapidly. In addition, a low Hveem stability value for a compacted mixture does not necessarily mean stability will not increase to acceptable values and remain so for a significant amount of simulated traffic testing in the gyratory machine.

The Hveem stabilometer was found to give variable results in this study when testing mixtures of high asphalt content at high number of revolutions. Under such conditions Hveem stabilometer tests on identical specimens would sometimes result in both very high and very low stability values. Whether this was due to a characteristic of the stabilometer test itself or whether supposedly identical specimens were in truth much different in stability has not been resolved. It would seem that such results might make it difficult to determine when failure conditions might arise in the bituminous material being tested.

Effect of Gyratory Testing on Aggregate Gradation

A short investigation was conducted as part of this research study to determine what effects, if any, the gyratory testing machine had on the aggregate gradation of specimens tested by the procedure selected as representative of normal traffic application. A number of specimens, tested through variable number of revolutions, were cut in half and a sieve analysis was performed on the aggregate after the asphalt was extracted from it. Figure 19 shows the results in terms of aggregate

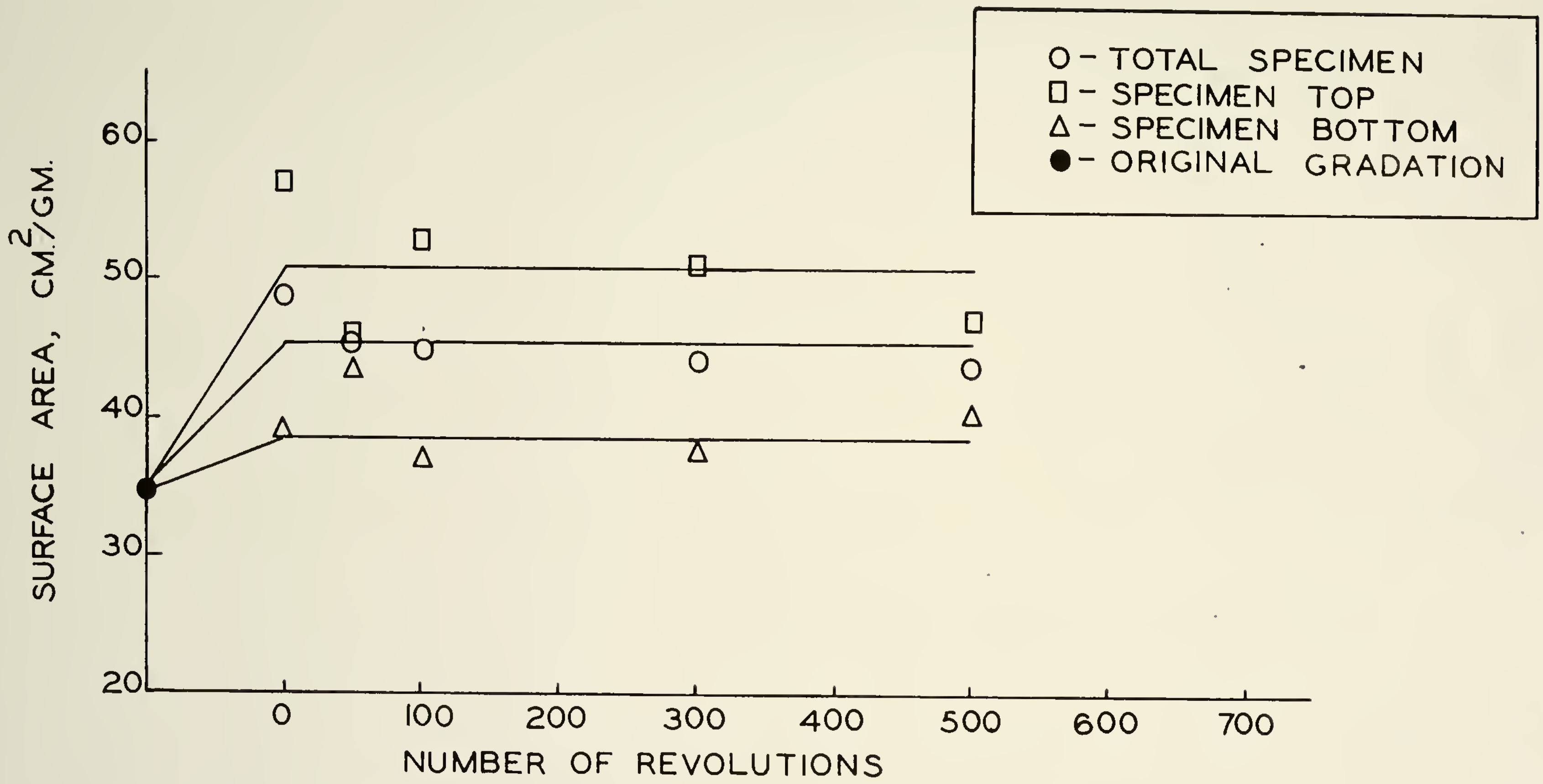

FIG. 19 AGGREGATE SURFACE AREA VS. NO. OF REVOLUTIONS

GRADATION A—5% ASPHALT, 80 PSI RAM PRESSURE, 60 PSI AIR PRESSURE, 1° GYRATION ANGLE surface area vs. number of revolutions. It is observed that kneading compaction caused aggregate breakage, most of which occurred in the upper half of the specimen, but that there was no evidence that additional aggregate degradation resulted from testing in the gyratory machine. It is concluded, therefore, that no significant aggregate degradation arose from use of the gyratory machine as a traffic simulating device in this study.

SUMMARY OF RESULTS AND CONCLUSIONS

This section presents conclusions that can be obtained from a summation of the results of this research study. They are based on data collected while using selected materials, procedures and equipment, and therefore may be representative of such conditions only. This study does not attempt to verify the conclusions outside of these boundaries. There has been no attempt to correlate the laboratory data to field conditions.

1. Use of the gyratory testing machine as a traffic simulating device produced changes in Hveem stability and bulk density of laboratory bituminous concrete specimens that are thought to be characteristic of property changes that may occur in actual pavements.

2. A suitable gyration angle for use in a traffic testing procedure applicable to highway pavement materials is apparently about one degree. Under the conditions of this study, a gyration angle of two degrees was found to be too severe. Its use resulted in a reduction of strength considered too rapid and forceful to represent the desired gradual breakdown of strength.

3. In general, the higher the ram pressure used in the gyratory machine operation, the lower was the maximum Hveem stability obtained during the range of revolutions of the test and the greater was the rate of stability loss following whatever maximum was reached. An additional effect was an increased bulk density of the test specimen.

4. It was postulated that the gyratory testing machine ram pressure represents tire pressures in a simulated traffic testing procedure.
5. For the test conditions of this study, increasing the upper roller air pressure from 45 psi to 85 psi had little effect on changing the initial gyrograph angle recorded, as compared to that obtained when the air pressure was increased from 30 psi to 45 psi.
6. The gyrograph recording of the angle of gyration the specimen is describing during the test had a poor sensitivity to the change in stability of the specimen. It did not give a reliable indication of whether the specimen strength was increasing or decreasing, nor the rate of such change. This sensitivity became greater for higher specimen asphalt content. Changes in the recorded gyration angle that did occur were difficult to determine because any change that does occur is gradual.
7. The higher the upper roller air pressure the more influencial it was in breaking down the lateral shoving resistance and, thus, stability of the test specimen. Higher values of air pressure had a greater effect on change in Hveem stability of test specimens than on change in their axial deformation or compactive densification.
8. The higher values of upper roller air pressure used in this study, 45 to 85 psi, are considered to be applicable for use in a traffic testing procedure. They caused breakdown of strength in the laboratory specimen which appeared to be similar

to that of the actual highway pavement and in a reasonable length of testing time. Increasing the air pressure lowered the number of revolutions through which the specimen would perform satisfactorily if an arbitrary minimum stability is selected.

9. At high pressures, operation with the air-filled roller approached conditions produced by operation with the fixed roller.
10. The testing of bituminous mixtures of variable asphalt content showed that, with aggregate gradation constant, the higher the asphalt content the lower was the maximum Hveem stability reached by a test specimen. Also, higher asphalt content specimens decreased to Hveem stability values below accepted minimum criteria at lower number of revolutions during the simulated traffic testing.
11. Simulated traffic testing in the gyratory machine resulted in major bulk density increase of test specimens occurring during the early number of revolutions. It reduced the air void content appreciably during the first 100 revolutions.
12. A gyratory machine simulated traffic testing procedure performed upon bituminous mixtures can serve as a basis for determining a range of asphalt content for which a mixture of a particular aggregate gradation can be expected to perform satisfactorily in service. A correlation study between laboratory test performance and field performance would be helpful in determining what "satisfactory performance" is represented by a laboratory procedure of gyratory machine simulated traffic testing.

13. The simulated traffic testing of the mixtures of different aggregate gradation at the same asphalt content showed quite clearly that a difference in performance could be expected from them.
14. The Hveem stability value alone did not give a reliable indication of how a mixture would perform in the gyratory machine. Some mixtures may have a satisfactory stability when initially compacted, but when subjected to simulated traffic testing they may lose stability and fail very rapidly.
15. The Hveem stabilometer was found to give variable results in this study when testing mixtures of high asphalt content at high number of revolutions. Under such conditions Hveem stabilometer tests on supposedly identical specimens would sometimes result in both very high and very low stability values, making it difficult to determine when failure conditions might arise in the bituminous material being tested. Whether this difference was due to stabilometer testing or to specimen variation was not determined.
16. No significant aggregate degradation arose from use of the gyratory machine as a traffic simulating device in this study.
17. The overall conclusion is that the gyratory testing machine shows promise that it can be used successfully as a traffic simulator device for the purpose of producing effects similar to rutting and shoving types of failure created in pavements by traffic action, when used in a manner such as described in this study. It is felt that variations in ram pressure and upper roller air pressure could be used to simulate various types of traffic

loadings. Testing procedure might call for determinations of stability for test specimens after specified numbers of revolutions as was done in this study. In contrast to using different types of traffic, a single combination of the variables might be used. In this case the number of revolutions required to cause failure would be used to determine under what type of traffic loading a mixture might be expected to perform satisfactorily.

SUGGESTIONS FOR FURTHER RESEARCH

This research study has presented the basis for the establishment of a procedure for use of the gyratory testing machine as a traffic simulating device. The use of this machine to evaluate the performance of bituminous concrete paving materials could act as a supplement to a design procedure which has as its purpose the selection of such a mixture from a standard compaction procedure.

It is necessary to know what the results from the simulated traffic testing procedure represent. A laboratory research study could be conducted for the purpose of collecting data on performance characteristics of a wide variety of bituminous concrete mixtures when tested in the gyratory machine by a procedure such as used in this study. It would involve the investigation of variable aggregate type and aggregate gradation as primary variables. Even though there were no field correlation involved with such a study, the amount of data collected would be large enough to serve as a direct evaluation of performance characteristics of all mixtures within this range of variation. Certainly a field correlation would be advantageous, but the collection of a large amount of laboratory performance data such as this would indicate what could be expected from any one mixture by its "location" within the range of laboratory performance data.

Another laboratory study that might produce interesting results would be an investigation to determine whether or not asphalt absorption into the aggregate portion of a bituminous mixture varies with number of revolutions in the gyratory testing machine.

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APPENDIX A

DATA
(Average Values)

APPENDIX A

TABLE 5

SURFACE AREA FACTORS

Fraction of Material		Factor
Passing	Retained	(cm^2/gm)
1/2"	3/8"	2.2
3/8"	#4	4.1
#4	#6	5.7
#6	#8	7.9
#8	#16	12.7
#16	#50	30.0
#50	#100	100.0
#100	#200	205.0
#200	Pan	615.0

Note: Assumed sp. gr. = 2.65. For values other than 2.65, multiply the above factors by 2.65/sp. gr.

TABLE 6

AGGREGATE SURFACE AREA FOR VARIABLE GYRATORY REVOLUTIONS

Gradation A - 5% Asphalt
80 psi Ram Pressure
60 psi Air Pressure

1^{o} Gyration Angle

Number of Revolutions	Aggregate Surface Area, Cm^2/gm			
	Original Gradation	Top-half of Specimen	Bottom-half of Specimen	Total Specimen
0	34.8	57.0	39.2	48.9
50		46.1	43.4	45.7
100		52.7	37.0	45.0
300		51.0	37.7	44.5
500		47.3	40.0	43.6

TABLE 7

HVEEM STABILITY AND BULK DENSITY FOR VARIABLE
GYRATORY MACHINE TESTING
GRADATION B - 6% ASPHALT

Hveem Stability

Gyratory Test Variables	Number of Revolutions						
	0	25	50	100	200	250	350
100 psi Ram Press 60 psi Air Press 1° Gyration Angle	37.0	40.5	37.7	43.4	37.6	32.3	20.3
100 psi Ram Press 45 psi Air Press 1° Gyration Angle	37.0	29.2	28.5	31.8	30.3		29.1
100 psi Ram Press 30 psi Air Press 1° Gyration Angle	37.0	30.1	33.6	31.5	31.7		19.5
100 psi Ram Press 60 psi Air Press 2° Gyration Angle	37.0	31.8	33.6	30.0	24.6		

Bulk Density (pcf)

100 psi Ram Press 60 psi Air Press 1° Gyration Angle	143.4	146.9	150.3	150.9	150.5	150.6	150.2
100 psi Ram Press 45 psi Air Press 1° Gyration Angle	143.4	148.8	148.4	149.0	149.6		150.2
100 psi Ram Press 30 psi Air Press 1° Gyration Angle	143.4	148.3	148.7	149.0	150.3		151.9
100 psi Ram Press 60 psi Air Press 2° Gyration Angle	143.4	149.0	149.9	152.2	151.2		

TABLE 8

HVEEM STABILITY FOR VARIABLE GYRATORY MACHINE TESTING
GRADATION A - 6% ASPHALT

Hveem Stability

Gyratory Test Variables	Number of Revolutions						
	0	25	50	100	300	500	700
100 psi Ram Press 60 psi Air Press 1° Gyration Angle	31.4	--	31.4	41.4	38.4	36.6	--
100 psi Ram Press 45 psi Air Press 1° Gyration Angle	31.4	35.8	33.2	33.7	44.5	36.9	--
80 psi Ram Press 85 psi Air Press 1° Gyration Angle	31.4	--	36.1	34.1	32.8	23.3	26.2
80 psi Ram Press 60 psi Air Press 1° Gyration Angle	31.4	34.7	38.2	40.1	43.2	37.7	34.9
80 psi Ram Press 45 psi Air Press 1° Gyration Angle	31.4	34.0	40.7	37.4	38.6	36.3	24.2
80 psi Ram Press 30 psi Air Press 1° Gyration Angle	31.4	--	34.6	33.8	41.2	40.2	40.0
150 psi Ram Press 85 psi Air Press 1° Gyration Angle	31.4	--	--	38.0	9.5	15.9	--

TABLE 9

BULK DENSITY FOR VARIABLE GYRATORY MACHINE TESTING
GRADATION A - 6% ASPHALT

Bulk Density (pcf)

Gyratory Test Variables	Number of Revolutions						
	0	25	50	100	300	500	700
100 psi Ram Press 60 psi Air Press 1° Gyration Angle	145.7	--	150.1	152.0	152.7	152.5	--
100 psi Ram Press 45 psi Air Press 1° Gyration Angle	145.7	149.1	149.6	150.6	151.6	152.3	--
80 psi Ram Press 85 psi Air Press 1° Gyration Angle	145.7	--	149.6	151.5	152.4	152.8	152.6
80 psi Ram Press 60 psi Air Press 1° Gyration Angle	145.7	148.6	149.2	149.5	150.8	151.3	151.0
80 psi Ram Press 45 psi Air Press 1° Gyration Angle	145.7	151.1	150.2	151.4	152.2	152.6	152.7
80 psi Ram Press 30 psi Air Press 1° Gyration Angle	145.7	--	149.9	149.7	150.7	150.8	150.9
150 psi Ram Press 85 psi Air Press 1° Gyration Angle	145.7	--	--	151.9	152.7	153.3	--

TABLE 10

% AXIAL DEFORMATION FOR VARIABLE UPPER ROLLER AIR PRESSURE - GRADATION A

6% Asphalt
80 psi Ram Pressure
1° Gyration Angle

% Axial Deformation

Number of Revolutions	Upper Roller Air Pressure (psi)			
	30	45	60	85
0	0.0	0.0	0.0	0.0
5	0.5	0.4	0.5	0.5
10	0.6	0.8	0.8	0.7
25	1.0	1.2	1.2	1.2
50	1.2	1.6	1.6	1.7
100	1.5	2.1	2.0	2.2
200	1.9	2.6	2.6	2.8
300	2.2	2.9	2.9	3.1
400	2.4	3.1	3.1	3.2
500	2.5	3.3	3.2	3.3

TABLE 11

MEASUREMENTS OF GYROGRAPH ANGLE FOR VARIABLE
UPPER ROLLER AIR PRESSURE - GRADATION A

6% Asphalt
80 psi Ram Pressure
1^{o} Gyration Angle

Width of Gyrograph (Divisions)

Number of Revolutions	Upper Roller Air Pressure (psi)			
	30	45	60	85
0	3.5	7.0	6.7	6.2
10	3.8	7.3	6.7	6.2
50	4.6	7.8	6.7	6.3
100	5.0	8.0	6.7	6.3
150	5.3	8.3	6.8	6.3
200	5.6	8.4	6.8	6.3
300	6.1	8.6	7.1	6.5
400	6.7	9.5	7.6	7.1
500	6.9	10.0	8.1	7.6
600				7.8
700	7.2			8.1

TABLE 12

HVEEM STABILITY AND BULK DENSITY FOR GRADATION A
VARYING ASPHALT CONTENT

80 psi Ram Pressure, 60 psi Air Pressure, 1° Gyration Angle

Hveem Stability

Asphalt Content, %	Number of Revolutions						
	0	50	100	300	500	700	1000
6.0	31.4	38.2	40.1	43.2	37.7	34.9	--
5.0	29.0	37.7	42.1	47.2	44.4	45.1	35.0
4.0	35.2	37.6	40.7	43.9	49.4	49.1	47.1

Bulk Density (pcf)

6.0	145.7	149.2	149.5	150.8	151.3	151.0	--
5.0	147.3	149.0	150.8	150.6	150.7	149.1	149.6
4.0	141.7	145.4	144.6	146.6	146.7	145.4	145.7

TABLE 13

HVEEM STABILITY AND BULK DENSITY FOR GRADATION D
VARYING ASPHALT CONTENT

80 psi Ram Pressure, 60 psi Air Pressure, 1° Gyration Angle

Hveem Stability

Asphalt Content %	Number of Revolutions						
	0	50	100	300	500	700	1000
5.0	30.7	37.4	42.8	41.9	44.8	41.9	--
4.5	35.1	44.2	47.8	51.0	50.4	45.3	34.1
4.0	34.7	45.7	46.7	49.8	50.5	53.6	57.2

Bulk Density (pcf)

5.0	147.5	148.6	149.2	150.2	150.0	150.1	--
4.5	146.3	148.3	148.9	149.2	149.6	150.7	151.6
4.0	143.8	145.6	146.6	148.1	149.1	148.1	148.7

TABLE 14

MEASUREMENTS OF GYROGRAPH ANGLE FOR VARIABLE ASPHALT CONTENT - GRADATION A

80 psi Ram Pressure
60 psi Air Pressure
1° Gyration Angle

Width of Gyrograph (Divisions)

Number of Revolutions	% Asphalt Content					
	4		5		6	
0	7.0	6.6	7.8	7.1	6.6	7.8
10	6.3	6.3	7.8	6.5	6.6	7.8
25	6.3	6.2	7.8	6.5	6.6	7.9
50	6.3	6.2	7.8	6.5	6.8	8.1
100	6.2	6.2	7.8	6.7	6.9	8.4
150	6.1	6.2	7.9	6.8	7.0	8.5
200	6.2	6.2	8.1	7.0	7.1	8.7
250	6.2	6.2	8.2	7.1	7.2	8.9
300	6.3	6.2	8.3	6.9	7.2	9.0
350	6.4	6.2	8.5	7.1	7.2	9.1
400	6.4	6.2	8.6	7.2	7.2	9.2
500	6.5	6.2	8.7	7.1	7.3	9.3
700	6.6	6.2	8.8	7.1	7.4	9.6
1000	6.6	6.2				

TABLE 15

% AXIAL DEFORMATION FOR VARIABLE ASPHALT CONTENT
GRADATION A

80 psi Ram Pressure
60 psi Air Pressure
1° Gyration Angle

% Axial Deformation

Number of Revolutions	% Asphalt Content		
	4	5	6
0	0.0	0.0	0.0
5	0.6	0.5	0.5
10	0.9	0.7	0.8
25	1.3	1.1	1.3
50	1.6	1.5	1.6
100	2.0	1.8	2.0
150	2.2	2.1	2.3
200	2.4	2.2	2.4
250	2.5	2.3	2.6
300	2.6	2.5	2.7
350	2.7	2.5	2.8
400	2.8	2.6	2.9
500	2.9	2.8	3.1
600	3.0	2.9	3.2
700	3.1	3.0	3.3
800	3.2		
900	3.3		
1000	3.3		

TABLE 16

% AXIAL DEFORMATION FOR VARIABLE ASPHALT CONTENT
GRADATION D

80 psi Ram Pressure
60 psi Air Pressure
1° Gyration Angle

% Axial Deformation

Number of Revolutions	% Asphalt Content 4.0	4.5	5.0
0	0.0	0.0	0.0
5	0.4	0.6	0.4
10	0.7	0.9	0.7
25	1.2	1.4	1.2
50	1.7	1.8	1.6
100	2.2	2.2	2.1
150	2.5	2.6	2.4
200	2.8	2.8	2.6
250			2.8
300	3.2	3.1	2.9
400	3.5	3.4	3.2
500	3.6	3.6	3.4
600	3.8	3.8	3.5
700	4.0	4.0	3.7
800	4.1	4.1	
1000	4.4	4.4	

APPENDIX B

DATA
(Individual Test Results)

APPENDIX B

TABLE 17

HVEEM STABILITY AND BULK DENSITY (UN-COATED AND PARAFFIN-COATED) FOR GRADATION H, 6% ASPHALT

80 psi Ram Pressure, 60 psi Air Pressure, 1° Gyration Angle

	Number of Revolutions				
	0	50	100	200	300
Hveem Stability	23.9	25.1	30.0	26.8	11.3
Bulk-Density (un-coated specimen)	150.8	151.2	151.4	152.0	152.5
Bulk-Density (paraffin-coated specimen)	149.6	151.1	152.0	152.3	152.6

TABLE 18

HVEEM STABILITY AND BULK DENSITY FOR VARIABLE GYRATORY MACHINE TESTING, GRADATION B - 6% ASPHALT
(Individual Test Results)

Hveem Stability

Gyratory Test Variables	Number of Revolutions						
	0	25	50	100	200	250	350
100 psi Ram Press 60 psi Air Press 1° Gyration Angle	37.3	40.9	36.5	43.6	38.2	20.3	18.0
	36.8	40.1	38.8	43.2	37.0	53.2	22.5
			31.0			23.2	
100 psi Ram Press 45 psi Air Press 1° Gyration Angle		26.7	30.7	33.3	28.8		25.6
		31.4	26.3	30.3	31.9		32.7
100 psi Ram Press 30 psi Air Press 1° Gyration Angle		33.2	33.4	35.2	35.8		21.1
		26.9	33.9	27.7	27.6		12.7
			42.1				24.8
100 psi Ram Press 60 psi Air Press 2° Gryation Angle		31.8	33.6	30.0	24.6		

Bulk Density (pcf)

Gyratory Test Variables	0	25	50	100	200	250	350
100 psi Ram Press 60 psi Air Press 1° Gyration Angle	141.1	147.8	150.0	150.8	147.0	150.1	150.1
	142.8	146.1	151.0	151.0	150.5	150.9	150.2
			149.8			150.8	
100 psi Ram Press 45 psi Air Press 1° Gyration Angle		148.8	148.8	150.0	150.1		151.0
		148.8	147.9	147.9	149.1		149.1
100 psi Ram Press 30 psi Air Press 1° Gyration Angle		146.8	149.0	149.0	150.8		150.0
		149.8	149.0	147.4	149.7		152.6
			148.0				153.0
100 psi Ram Press 60 psi Air Press 2° Gyration Angle		149.0	149.9	152.2	151.2		

TABLE 19

HVEEM STABILITY FOR VARIABLE GYRATORY MACHINE TESTING
GRADATION A - 6% ASPHALT
(Individual Test Results)

Hveem Stability

Gyratory Test Variables	Number of Revolutions						
	0	25	50	100	300	500	700
100 psi Ram Press 60 psi Air Press 1° Gyration Angle	31.0 31.7		31.4	41.4	38.4	27.7 45.5	
100 psi Ram Press 45 psi Air Pres 1° Gyration Angle		32.1 39.5	30.0 35.4 34.3	31.5 35.8	49.4 39.7	36.9	
80 psi Ram Press 85 psi Air Press 1° Gyration Angle			34.2 38.0	30.4 37.8	44.2 21.4	24.9 21.6	35.5 23.6 19.6
80 psi Ram Press 60 psi Air Press 1° Gyration Angle		36.6 34.7 32.7	41.1 35.3 38.1	42.0 38.8 39.6	41.1 45.2	37.2 39.8 36.0	33.3 36.2 35.3
80 psi Ram Press 45 psi Air Press 1° Gyration Angle		34.0 34.1	41.5 40.0	37.1 37.7	35.7 43.7 35.8 39.4	29.3 30.6 32.8 43.1 45.8	36.9 11.4

TABLE 19 (CONT.)

HVEEM STABILITY FOR VARIABLE GYRATORY MACHINE TESTING
GRADATION A - 6% ASPHALT
(Individual Test Results)

Hveem Stability

Gyratory Test Variables	Number of Revolutions						
	0	25	50	100	300	500	700
80 psi Ram Press 30 psi Air Press 1° Gyration Angle			34.4 34.9	33.6 32.9 34.8	42.5 40.0	39.5 40.9	41.6 38.5
150 psi Ram Press 85 psi Air Press 1° Gyration Angle				46.1 29.9	9.5	15.9	

TABLE 20

BULK DENSITY FOR VARIABLE GYRATORY MACHINE TESTING
GRADATION A - 6% ASPHALT
(Individual Test Results)

Bulk Density (pcf)

Gyratory Test Variables	Number of Revolutions						
	0	25	50	100	300	500	700
100 psi Ram Press 60 psi Air Press 1° Gyration Angle	144.9 146.5		150.1	152.0	152.7	153.0 152.0	
100 psi Ram Press 45 psi Air Press 1° Gyration Angle		151.1 147.2	150.0 149.8 149.1	150.9 149.8	151.1 152.2	152.3	
80 psi Ram Press 85 psi Air Press 1° Gyration Angle			151.0 148.2	152.0 151.0	152.1 152.8	153.0 152.7	152.4 152.7 152.8
80 psi Ram Press 60 psi Air Press 1° Gyration Angle		147.9 149.2 148.6	148.5 150.8 148.2	147.5 151.0 149.9	151.8 149.8	152.2 152.3 149.5	150.2 150.9 151.9
80 psi Ram Press 45 psi Air Press 1° Gyration Angle		151.3 151.0	151.0 149.3	150.9 151.9	152.5 152.0 151.9 152.2	152.4 153.0 152.3 152.8 152.3	152.0 153.3

TABLE 20 (CONT.)

BULK DENSITY FOR VARIABLE GYRATORY MACHINE TESTING
GRADATION A - 6% ASPHALT
(Individual Test Results)

Bulk Density (pcf)

Gyratory Test Variables	Number of Revolutions						
	0	25	50	100	300	500	700
80 psi Ram Press 30 psi Air Press 1° Gyration Angle			149.0 150.9	148.2 151.2 149.8	150.3 151.1	150.7 150.9	151.0 150.7
150 psi Ram Press 85 psi Air Press 1° Gyration Angle				151.7 152.0	152.7	153.3	

TABLE 21

HVEEM STABILITY AND BULK DENSITY FOR GRADATION A - VARYING ASPHALT CONTENT
(Individual Test Results)

80 psi Ram Pressure, 60 psi Air Pressure, 1° Gyration Angle

Hveem Stability

Asphalt Content, %	Number of Revolutions						
	0	50	100	300	500	700	1000
6	31.0	41.1	42.0	41.1	37.2	33.3	
	31.7	35.3	38.8	45.2	39.8	36.2	
		38.1	39.6		36.0	35.3	
5	30.6	42.0	37.6	48.5	49.0	40.1	27.3
	29.3	33.7	45.0	45.9	39.2	43.4	42.7
	27.0	37.5	43.8	47.2	40.6	44.8	
					49.0	52.0	
4	38.6	36.5	41.7	47.9	49.4	51.7	50.0
	33.3	41.4	42.5	45.4	44.9	47.6	45.3
	33.6	35.0	38.0	38.4	53.9	48.0	46.1

Bulk Density (pcf)

Asphalt Content, %	0	50	100	300	500	700	1000
6	144.9	148.5	147.5	151.8	152.2	150.2	
	146.5	150.8	151.0	149.8	152.3	150.9	
		148.2	149.9		149.5	151.9	
5	147.1	149.6	151.8	150.6	151.2	148.6	151.9
	148.2	146.0	149.8	151.2	151.0	148.0	147.3
	146.7	148.4	150.8	150.0	150.8	148.8	
					149.7	150.0	
4	141.5	144.7	144.8	146.8	145.8	147.0	146.9
	141.8	147.0	148.0	150.6	149.6	148.2	144.8
	141.7	144.5	141.0	142.5	144.8	141.0	145.4

TABLE 22

BULK DENSITY (BASED ON SPECIMEN AXIAL HEIGHTS) FOR GRADATION A - VARYING ASPHALT CONTENT
(Individual Test Results)

80 psi Ram Pressure, 60 psi Air Pressure, 1° Gyration Angle

Bulk Density (pcf)

Asphalt Content, %	Number of Revolutions						
	0	50	100	300	500	700	1000
6	143.6	147.6	146.6	154.7	152.8	152.0	
	146.4	150.0	150.0	152.3	152.3	152.4	
		150.2	153.8		151.2	151.5	
5	143.3	149.6	151.9	151.5	150.8	150.9	153.4
	144.2	148.0	149.8	149.8	152.8	150.5	148.7
	146.3	146.8	149.7	150.9	150.0	151.2	
					150.8	151.9	
4	143.2	147.0	146.7	149.8	148.1	149.2	148.8
	142.5	148.8	149.4	152.2	150.4	155.8	145.1
	141.2	144.7	142.2	144.8	145.1	140.3	147.0

TABLE 23

HVEEM STABILITY AND BULK DENSITY FOR GRADATION D - VARYING ASPHALT CONTENT
(Individual Test Results)

80 psi Ram Pressure, 60 psi Air Pressure, 1° Gyration Angle

Hveem Stability

Asphalt Content, %	Number of Revolutions						
	0	50	100	300	500	700	1000
5.0	27.5	34.9	40.1	37.1	46.1	44.5	
	33.8	41.3	39.9	43.7	50.0	28.2	
	34.2	40.7	47.8	49.7	39.8	51.6	
	27.9	32.7	43.5	37.1	43.4	43.4	
	30.1						
4.5	31.8	43.2	49.1	52.7	45.6	40.3	17.1
	38.5	43.0	47.4	44.8	52.9	46.5	50.5
		46.5	46.9	55.6	52.6	49.1	34.8
4.0	35.1	49.3	48.6	46.8	39.2	57.3	57.4
	33.3	44.1	46.5	49.9	45.9	54.5	57.5
	35.7	43.8	45.0	52.6	55.1	48.9	56.8

Bulk Density (pcf)

Asphalt Content, %	0	50	100	300	500	700	1000
5.0	148.9	149.0	149.3	150.4	149.0	149.8	
	145.9	148.0	149.0	149.2	149.5	150.0	
	146.3	148.5	148.0	150.4	151.0	151.0	
	147.3	149.1	150.4	150.4	150.4	150.4	
	149.1						
4.5	146.0	147.9	147.9	149.1	149.8	150.4	152.3
	146.6	148.5	148.5	150.0	149.8	150.7	151.0
		148.5	150.4	148.5	149.1	151.0	151.6
4.0	143.2	145.4	146.6	147.9	149.8	148.5	149.1
	142.9	146.0	146.6	149.1	149.7	149.1	148.5
	145.4	145.4	146.6	147.3	148.5	146.6	148.5

TABLE 24

BULK DENSITY (BASED ON SPECIMEN AXIAL HEIGHTS) FOR GRADATION D - VARYING ASPHALT CONTENT
(Individual Test Results)

80 psi Ram Pressure, 60 psi Air Pressure, 1° Gyration Angle

Bulk Density (pcf)

Asphalt Content, %	Number of Revolutions						
	0	50	100	300	500	700	1000
5.0	147.6	148.7	149.8	150.9	153.4	152.0	
	146.8	151.8	152.7	151.4	152.8	154.1	
	149.0	150.0	150.8	152.1	153.7	153.8	
	148.9	150.8	151.2	153.2	153.4	152.8	
	149.0						
4.5	147.0	149.0	151.2	152.5	152.5	154.2	154.6
	147.1	150.2	151.8	153.2	151.0	153.3	153.8
		149.4	150.1	150.3	151.3	154.0	154.0
4.0	145.2	149.0	150.8	151.2	153.8	152.3	152.0
	144.5	149.1	150.1	151.4	153.4	152.8	152.6
	148.3	148.2	150.0	150.8	151.4	148.8	152.5

TABLE 25

HVEEM STABILITY AND BULK DENSITY (UN-COATED AND PARAFFIN-COATED) FOR GRADATION H, 6% ASPHALT
(Individual Test Results)

80 psi Ram Pressure, 60 psi Air Pressure, 1° Gyration Angle

	Number of Revolutions				
	0	50	100	200	300
Hveem Stability	23.8 26.7 21.2	29.2 21.5 24.5	33.4 29.6 27.1	33.4 20.3	8.3 14.8 10.7
Bulk-Density (un-coated specimen)	151.5 150.0 150.9	151.4 151.1 151.2	150.9 151.0 152.3	152.4 151.5 152.8	152.7 152.0 152.7
Bulk-Density (paraffin-coated specimen)	145.0 149.8 149.3	145.3 151.3 150.8	151.9 152.0 152.2	152.1 152.3 152.5	146.3 152.4 152.7